August 3, 2020

Vehicle Performance Study

I. ACCIDENT

NTSB Number: DCA17PM018
Location: Sagami Nada Bay off Izu Peninsula, Honshu Island, Japan
Date: June 17, 2017
Time: 0130:32 Local Time
Vessel 1:   *USS Fitzgerald*, Arleigh Burke-class destroyer
Vessel 2:   Motor Vessel *ACX Crystal*, Operated by Sea Quest Ship Management, Inc.

II. VEHICLE PERFORMANCE SPECIALIST

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Vehicle Performance Engineer
Office of Research and Engineering
National Transportation Safety Board (NTSB)

1.0 INTRODUCTION

The NTSB Office of Marine Safety requested assistance reconstructing and evaluating the pre-collision paths of the *USS Fitzgerald* and the Motor Vessel (MV) *ACX Crystal*. The collision between these two vessels was reconstructed using own-ship data recorded by the MV *ACX Crystal* and *USS Fitzgerald* position data recorded by the *Wan Hai 266*. This study documents the results of the vessel collision path reconstruction as well as three alternate scenarios which examined the respective effects of each ship (in turn) omitting its last pre-collision course change and both ships omitting their last pre-collision course change. Each vessel path reconstruction scenario is documented by an image sequence summary and an animated .gif file.

See the NTSB Accident Docket for a summary of the accident.

2.0 FACTUAL EVIDENCE

2.1 Vessel Characteristics

Post-accident photographs of the *USS Fitzgerald* and the MV *ACX Crystal* are shown in Figures 1(a) and 1(b).

Figure 1(a): *USS Fitzgerald*, Arleigh Burke-class destroyer
Source: https://www.ocregister.com/2017/06/16/uss-fitzgerald-collides-with-merchant-ship-off-japan-7-us-navy-sailors-reportedly-missing/
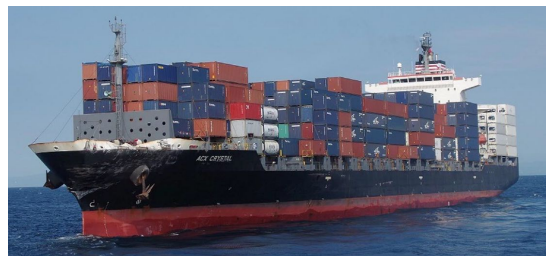

Figure 1(b): MV *ACX Crystal*, container ship
Image available on NTSB public docket

In addition to the voyage paths reconstructed for the *USS Fitzgerald* and the MV *ACX Crystal*, voyage paths were reconstructed for the *Wan Hai 266* and the *Maersk Evora*. Vessel descriptions, their International Maritime Organization (IMO) identification numbers, dimensions, gross tonnage, and direction of travel prior to the collision are summarized in Table 1.

Table 1: Summary of vessel characteristics

Vessel Name	Description	IMO number	Length, feet	Beam, feet	Draft, feet	Gross Tonnage	Direction of Travel
USS Fitzgerald	Arleigh Burke-class destroyer	---	505	66	31	9,000	South
ACX Crystal	Container ship	9360611	730	99	39	29,060	East
Wan Hai 266	Container ship	9233636	650	92	---	18,870	East
Maersk Evora	Container ship	9458080	1,202	158	49	141,715	Northeast

2.2 Recorded Voyage Data

The commercial vessel position data available to the investigation included own-ship radar images, Voyage Data Recorder (VDR) data, Global Positioning System (GPS) data, and handwritten position logs. The *USS Fitzgerald* data made available to the investigation included screenshots of Voyage Management System (VMS) data, unredacted bell book data, and handwritten log data.

2.3 Vessel Collision Path Reconstruction

Collision reconstruction data were available from the following sources:

1. Japan Transport Safety Board (JTSB) public report for this collision event (tabulated data for five vessels were reviewed, but JTSB data were not used in this study)
   https://www.mlit.go.jp/jtsb/eng-mar_report/2019/2017tk0009e.pdf
2. United States Navy (USN) public report for this collision event (data were reviewed, but USN data were not used in this study)
   https://s3.amazonaws.com/CHINFO/USS+Fitzgerald+and+USS+John+S+McCain+Collision+Reports.pdf
3. *Wan Hai 266* radar and GPS data (used for own-ship position and heading; bearing and range data were used to reconstruct *USS Fitzgerald* position)
4. MV *ACX Crystal* radar and GPS data (used for own-ship position and heading)
5. *USS Fitzgerald* VMS data (data were reviewed to validate calculated *USS Fitzgerald* position data derived from *Wan Hai 266* radar data, but protected USN VMS data were not used in this study)
6. *USS Fitzgerald* unredacted bell book data (data were reviewed, but USN unredacted bell book data were not used in this study)
7. *USS Fitzgerald* handwritten log data (data were reviewed, but USN handwritten log data were not used in this study)

The *USS Fitzgerald* position data for this study were derived from the *Wan Hai 266* radar (bearing and range) data. A comparison of the commercially-derived *USS Fitzgerald* position data to the VMS data and handwritten log data from the *USS Fitzgerald* affirmed that the vessel position data from the three sources were consistent. Of note, the *USS Fitzgerald* screenshots of VMS data and the unredacted bell book data are considered United States National Defense Information (NDI) and are protected from public release. Therefore, **none of the *USS Fitzgerald* NDI data were used to reconstruct the accident voyage or any portion of the alternate scenarios documented in this study.**

The derived heading information for the *USS Fitzgerald* near the point of collision has increased uncertainty due to sparse data samples; dynamic control inputs; complex hydrodynamic interaction; unvalidated vessel

response; and the high energy state. The mechanical witness mark evidence from each vessel, structural deformation models, and/or higher resolution data from the *USS Fitzgerald* need to be incorporated if vessel collision damage or collision energy dissipation are of central interest. These issues are beyond the scope of this vehicle performance study.

2.4 Alternate Scenario Vessel Path Reconstruction

Alternate simulation scenario requests from the NTSB Office of Marine Safety evolved over the course of the investigation. The original request was to determine if the bearing ring around MV *ACX Crystal's* radar image is corrected for parallax. The construction of a high-confidence model of vessel position as a function of time for both the MV *ACX Crystal* and the *USS Fitzgerald* enabled investigators to back-calculate and validate multiple bearing points extracted from the MV *ACX Crystal* radar, which showed that the bearing ring was corrected for parallax. Of equal importance, the model used to evaluate the parallax question was compatible with alternate scenario evaluation interests from marine operations investigators.

Three data-driven, alternate scenario vessel path reconstructions were developed:

1. *USS Fitzgerald* holds its previous course (does not change course from 190 to 200)
2. MV *ACX Crystal* holds its previous course (does not change course from 086 to 069)
3. MV *ACX Crystal* and *USS Fitzgerald* both hold their previous courses

The use of first principles, physics-based, data-driven simulation models and animation techniques enables investigators to evaluate the effects of hypothetical operational assumptions and the expected vessel response. Alternate scenario outcomes can be postulated, calculated, validated, and quantified.

The optional animation of simulation model results offers visual presentations with variable levels of detail that promote intuitive comprehension and interpretation by a much larger audience of accident/incident investigators, marine industry stakeholders, and members of the general public. The resulting simulation data can also be imported into third party applications (e.g., Rembrandt or other) for further evaluation by operational and/or human performance investigators to assess the effects of hypothetical crew actions/ inactions and response times on vessel behavior.

3.0 RESULTS

3.1 Vessel Path Reconstruction

Google Earth snapshots of the reconstructed vessel collision and vessel observer paths are shown in Figures 2 and 3, which respectively present a geographic overview and a zoomed-in view.

As indicated in Figures 2 and 3, the *USS Fitzgerald* was on a course of 190 until about 0122 when it began a course change to starboard. The destroyer completed its course change to 200 by about 0124. The *USS Fitzgerald* speed was about 19 to 20 knots between 0115 and 0130. The collision occurred at 0130:32. The factual evidence indicates that the *USS Fitzgerald* increased speed and maneuvered to port in the seconds prior to the collision.

The MV *ACX Crystal* was on a course of 086 until about 0116, when it began a course change to port. The container ship completed its course change to 069 by about 0119. The MV *ACX Crystal* was traveling at a speed of about 18 knots from 0115 up to the collision at 0130:32. The factual evidence indicates that the MV *ACX Crystal* maneuvered to starboard in the seconds prior to the collision.
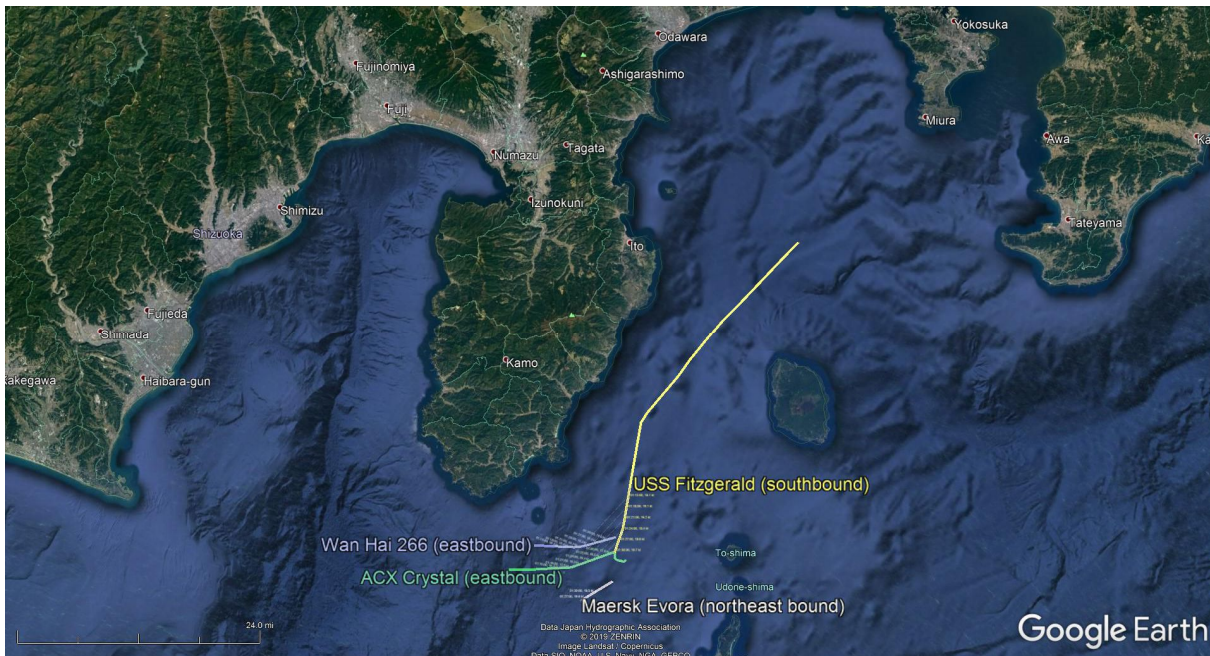
Figure 2: Overview of reconstructed vessel paths for the *USS Fitzgerald* (yellow), MV *ACX Crystal* (green), *Wan Hai 266* (blue), and *Maersk Evora* (white). True North is toward the top of the page. Actual vessel traffic in these waters was much more congested than depicted by the four paths shown.
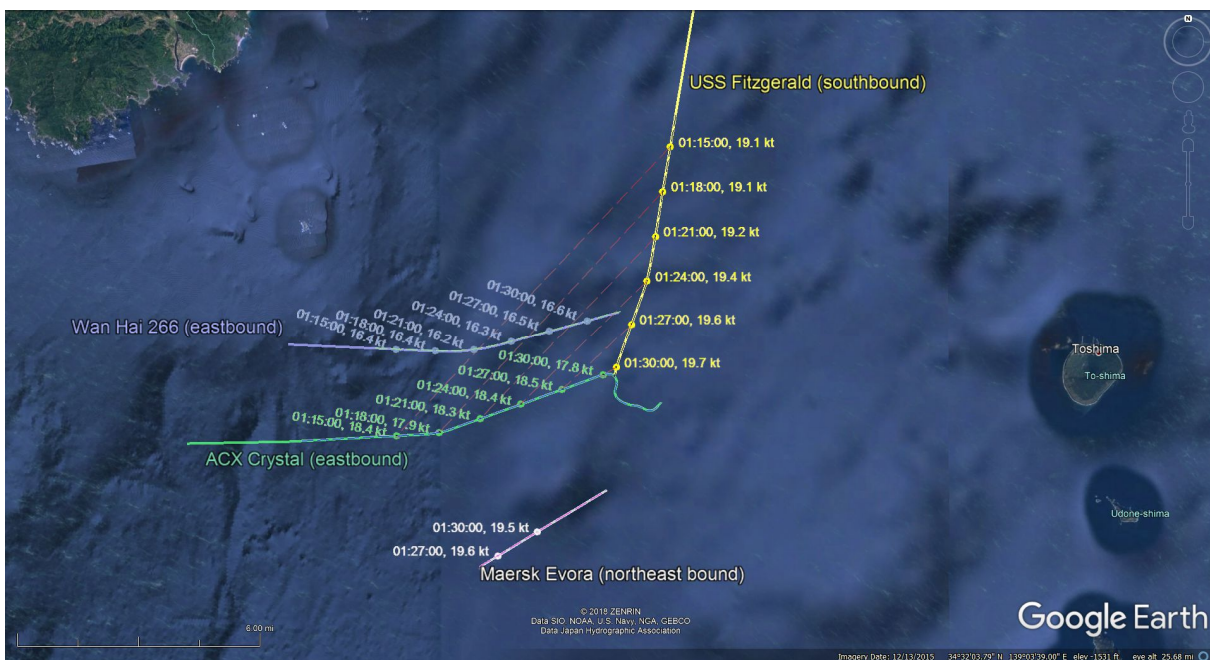

Figure 3: Zoomed-in view of reconstructed vessel paths as a function of time for the *USS Fitzgerald* (yellow), MV *ACX Crystal* (green), *Wan Hai 266* (blue), and *Maersk Evora* (white). True North is toward the top of the page. Actual vessel traffic in these waters was much more congested than depicted by the four paths shown.

3.2 Alternate Scenario Path Reconstruction (*USS Fitzgerald* holds its previous course)

If the *USS Fitzgerald* had held its previous course of 190 as the MV *ACX Crystal* followed its recorded pre-collision course, the *USS Fitzgerald* stern would have crossed in front of and cleared the projected position of the MV *ACX Crystal* bow by a distance of about 1,450 yards (about 0.7 nm).

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3.3 Alternate Scenario Path Reconstruction (MV *ACX Crystal* holds its previous course)

If the MV *ACX Crystal* had held its previous course of 086 as the *USS Fitzgerald* followed its recorded pre-collision course, the MV *ACX Crystal* stern would have crossed in front of and cleared the projected position of the *USS Fitzgerald* bow by a distance of about 3,300 yards (about 1.6 nm).

3.4 Alternate Scenario Path Reconstruction (MV *ACX Crystal* and *USS Fitzgerald* both hold previous courses)

If the *USS Fitzgerald* had held its previous course of 190 and the MV *ACX Crystal* had held its previous course of 086, the MV *ACX Crystal* stern would have crossed in front of and cleared the projected position of the *USS Fitzgerald* bow by a distance of about 1,520 yards (about 0.75 nm).

4.0 ATTACHMENTS

The vessel path reconstructions for the collision event and for each alternate scenario are documented by the corresponding sequence of images in Attachments 1-4 and the animated .gif file (highlighted in blue). The animated .gif file playback speed progresses from 32 times faster than real time to 8 times faster than real time to 2 times faster than real time. The radii of the concentric circles around each vessel depict distances of 0.25 nm (red), 0.50 nm (orange), 0.75 nm (yellow), and 1.0 nm (green), respectively. The animated .gif files may be viewed in most internet browsers (download the file from the NTSB public docket and load it into the internet browser from a local directory).

Attachment 1: Vessel path reconstruction
(Collision event)
NTSB_USS_Fitzgerald_MV_ACX_Crystal_Collision_Reconstruction_Animation_(Collision_Event).gif

Attachment 2: Alternate scenario vessel path reconstruction
(*USS Fitzgerald* holds its previous course)
NTSB_USS_Fitzgerald_MV_ACX_Crystal_Alternate_Scenario_Animation_(USS_Fitzgerald_Holds_Previous_Course).gif

Attachment 3: Alternate scenario vessel path reconstruction
(MV *ACX Crystal* holds its previous course)
NTSB_USS_Fitzgerald_MV_ACX_Crystal_Alternate_Scenario_Animation_(MV_ACX_Crystal_Holds_Previous_Course).gif

Attachment 4: Alternate scenario vessel path reconstruction
(Each vessel holds its previous course)
NTSB_USS_Fitzgerald_MV_ACX_Crystal_Alternate_Scenario_Animation_(MV_ACX_Crystal_and_USS_Fitzgerald_Hold_Previous_Course).gif

Attachment 1
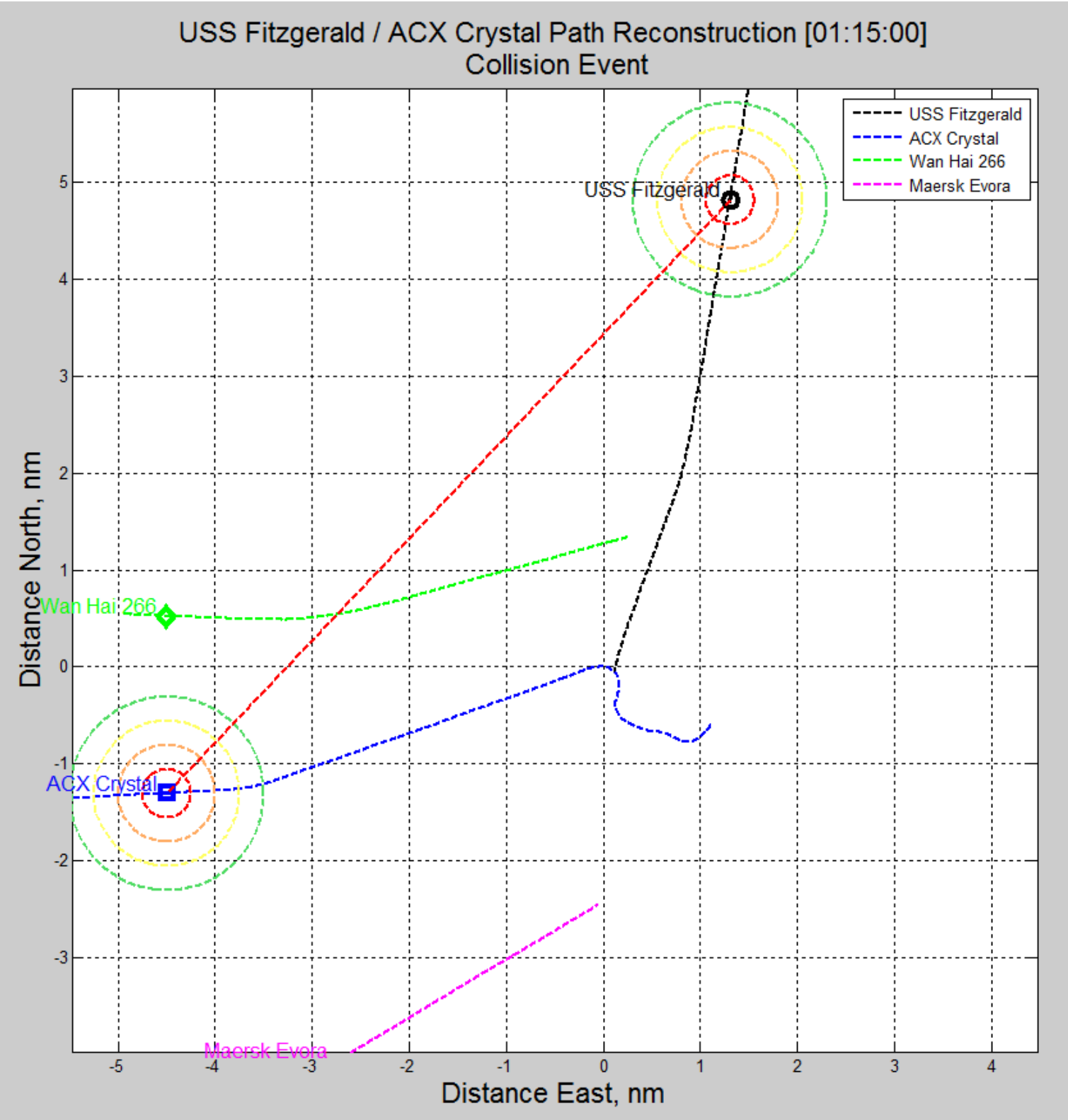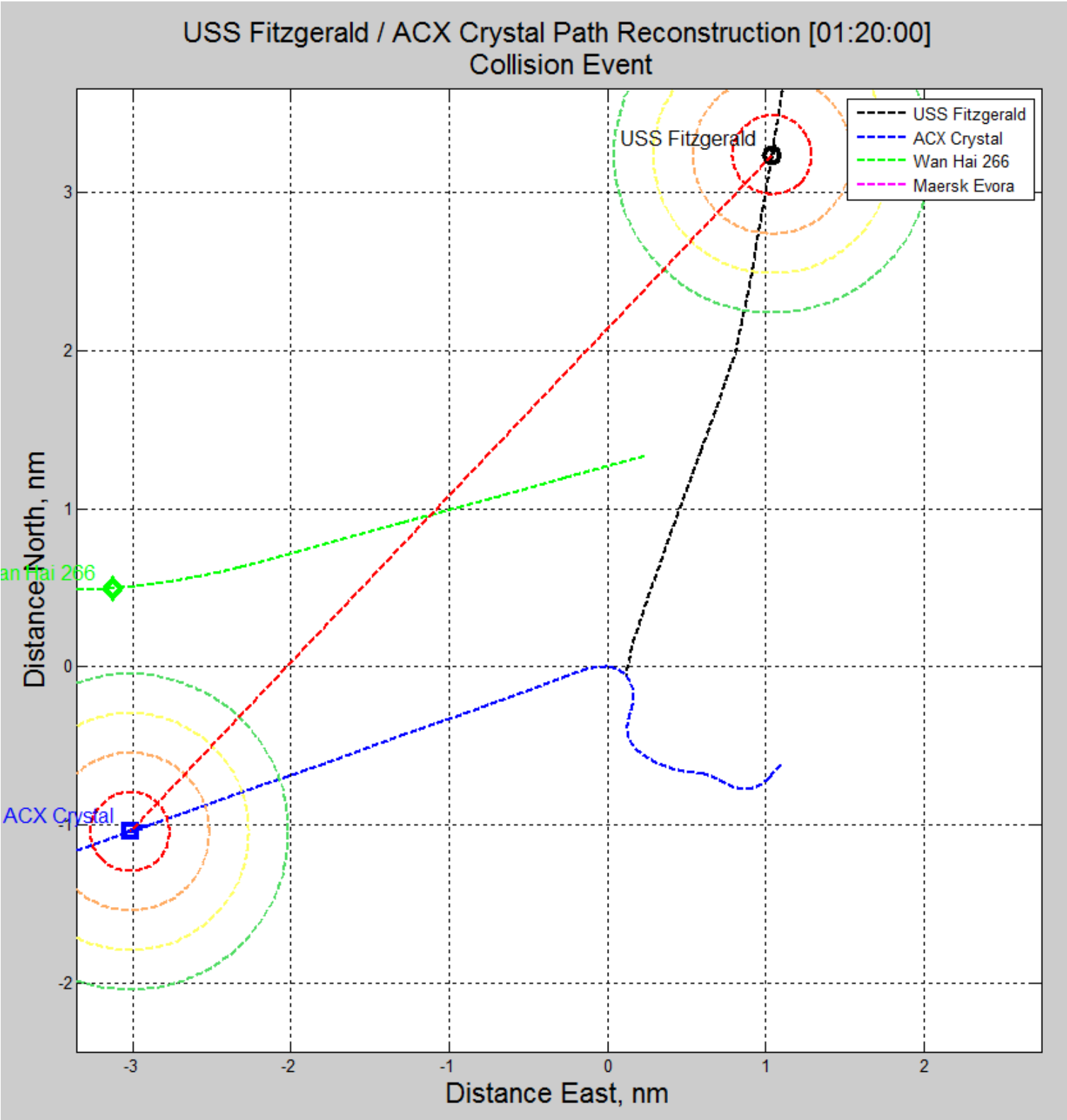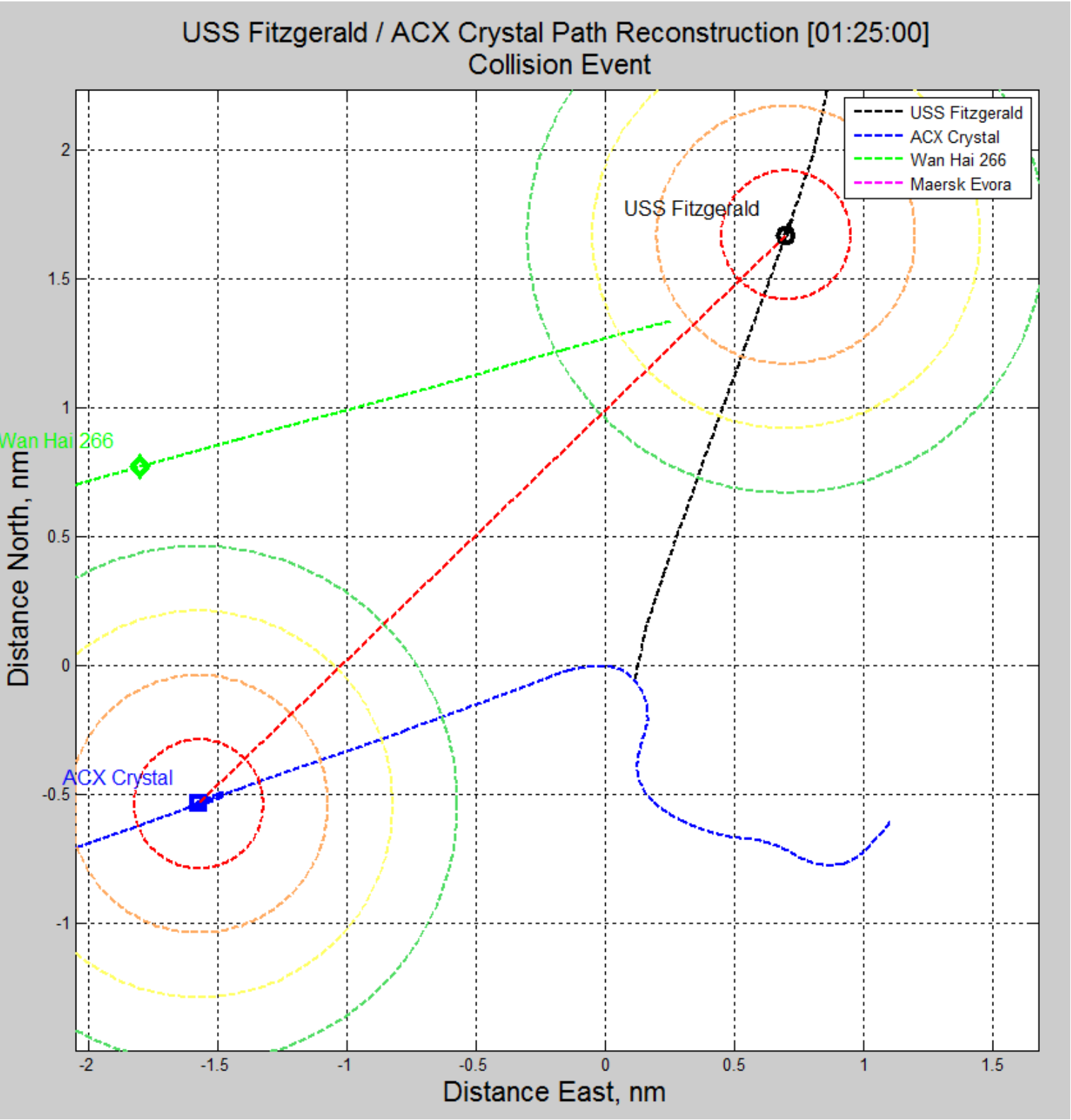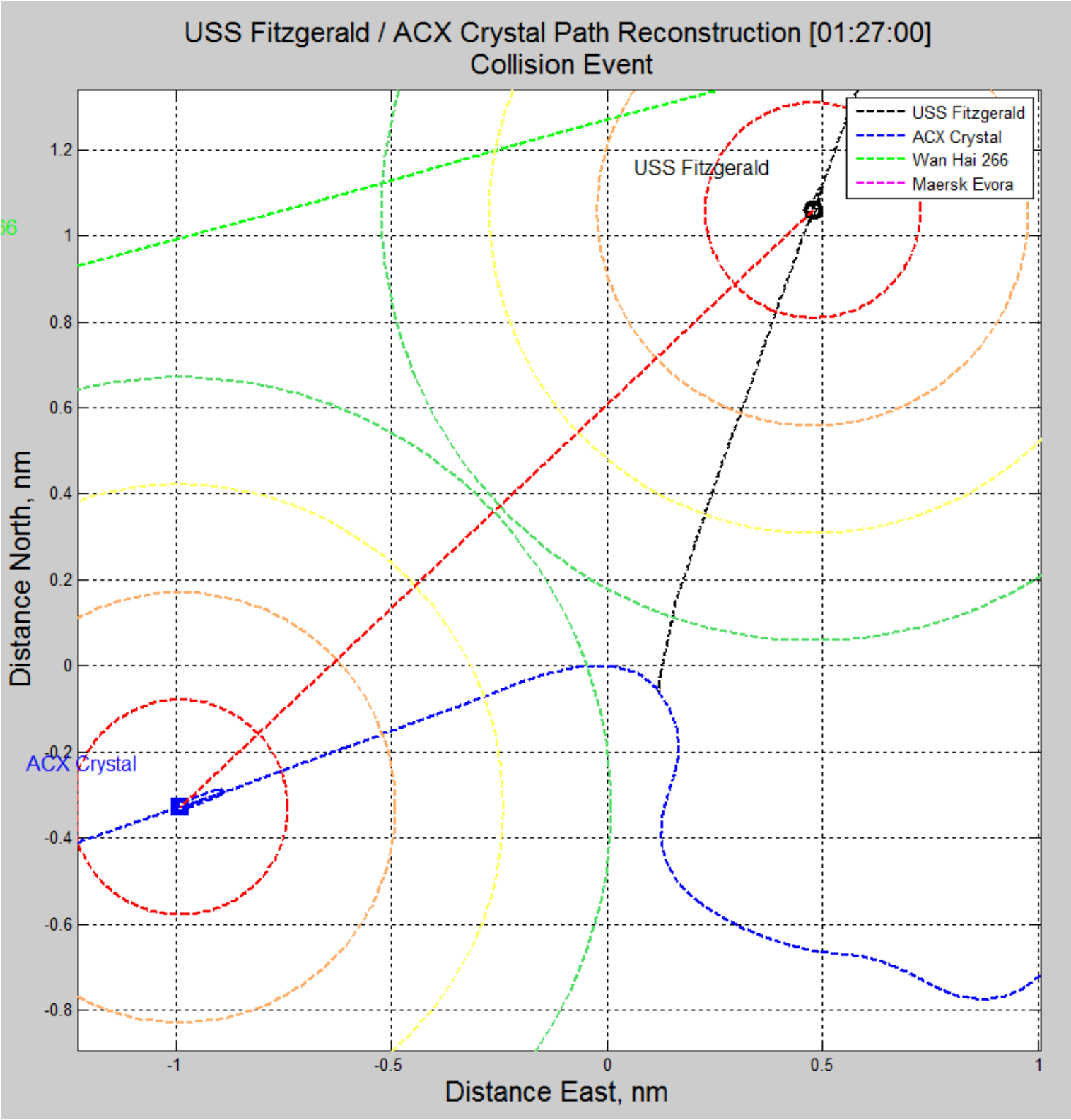
Vessel path reconstruction
(Collision event)

Figure A1.1: 01:15:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
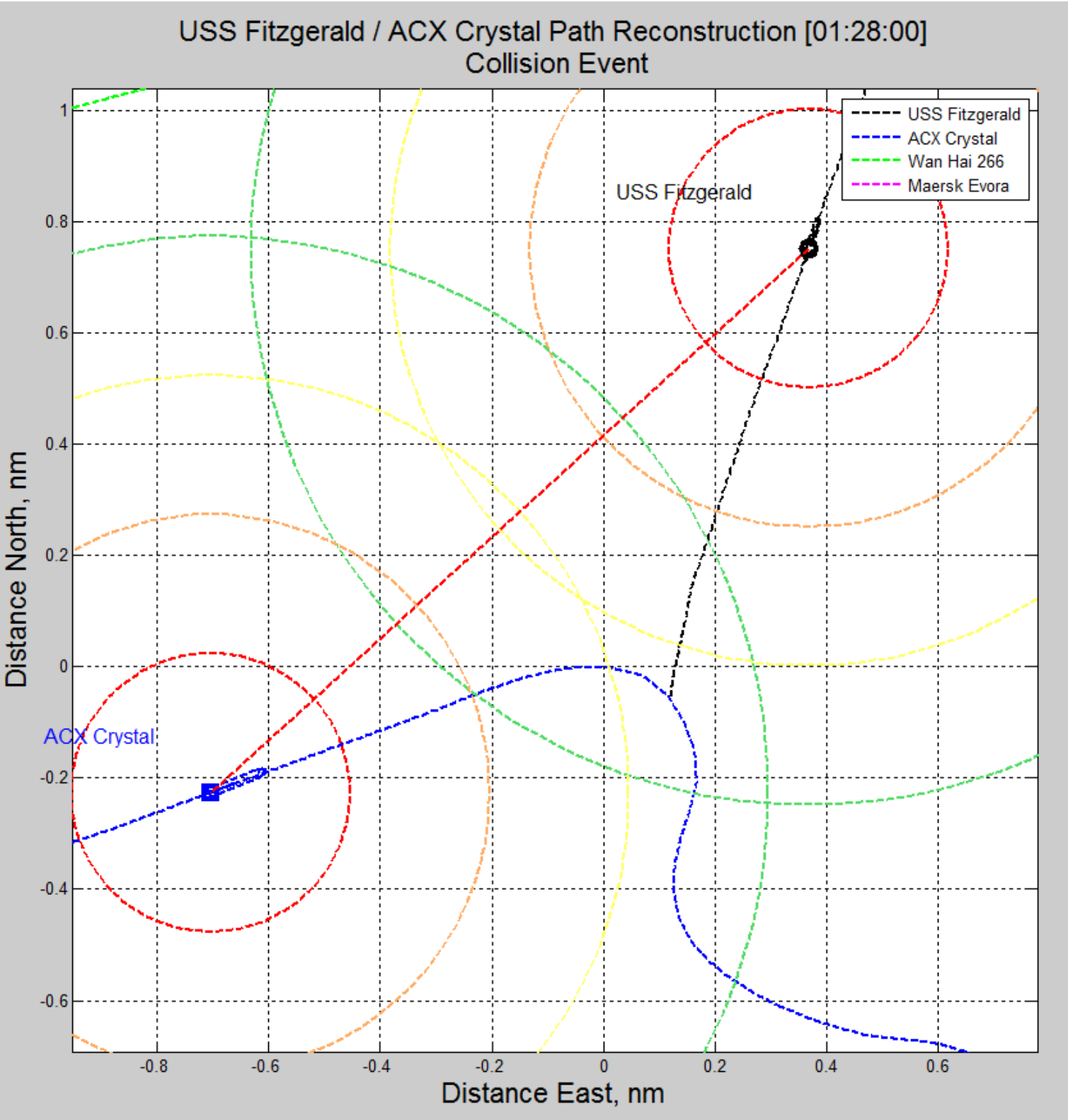
Figure A1.2: 01:20:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
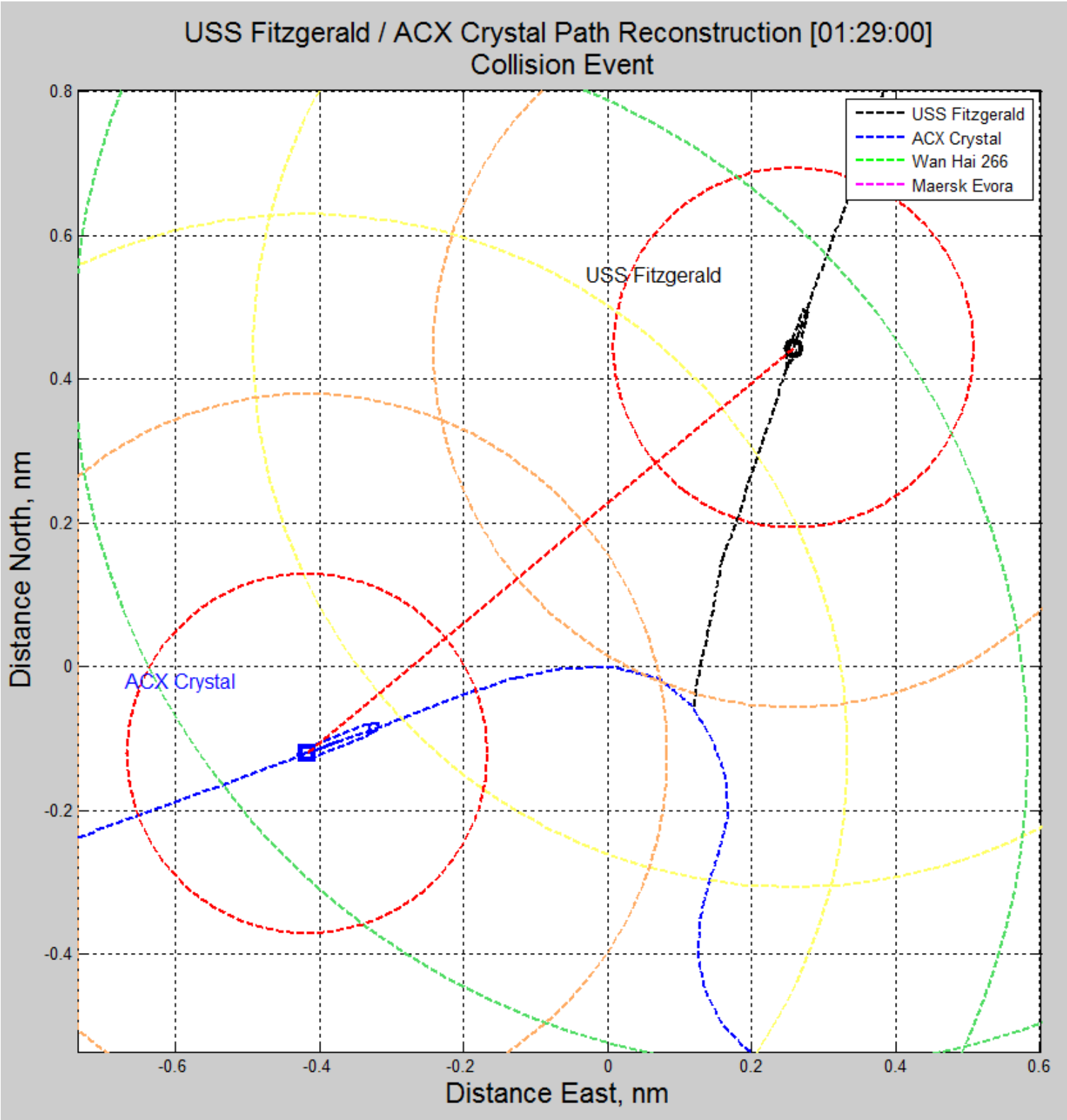
A1.2

Figure A1.3: 01:25:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
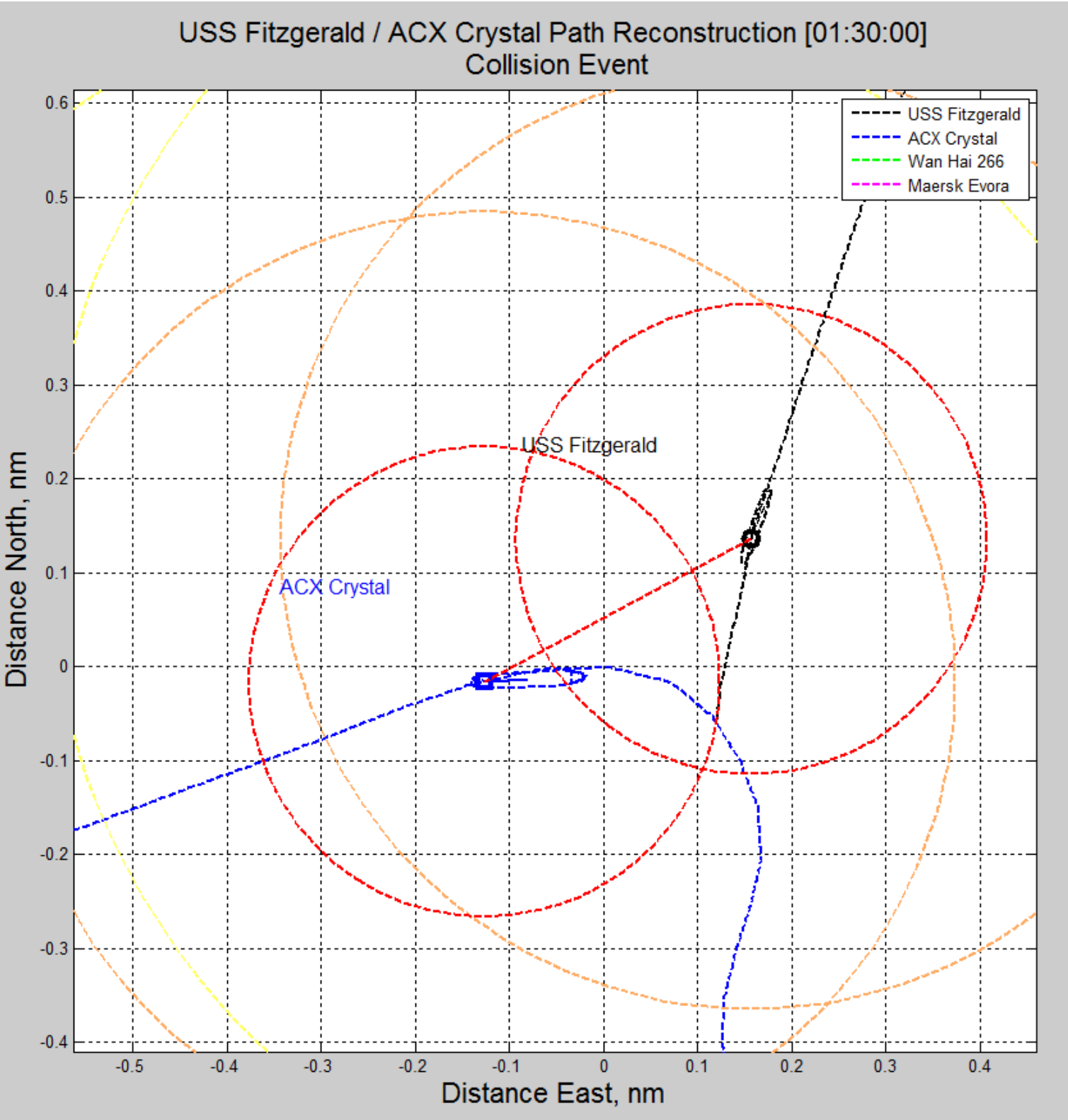
Figure A1.4: 01:27:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
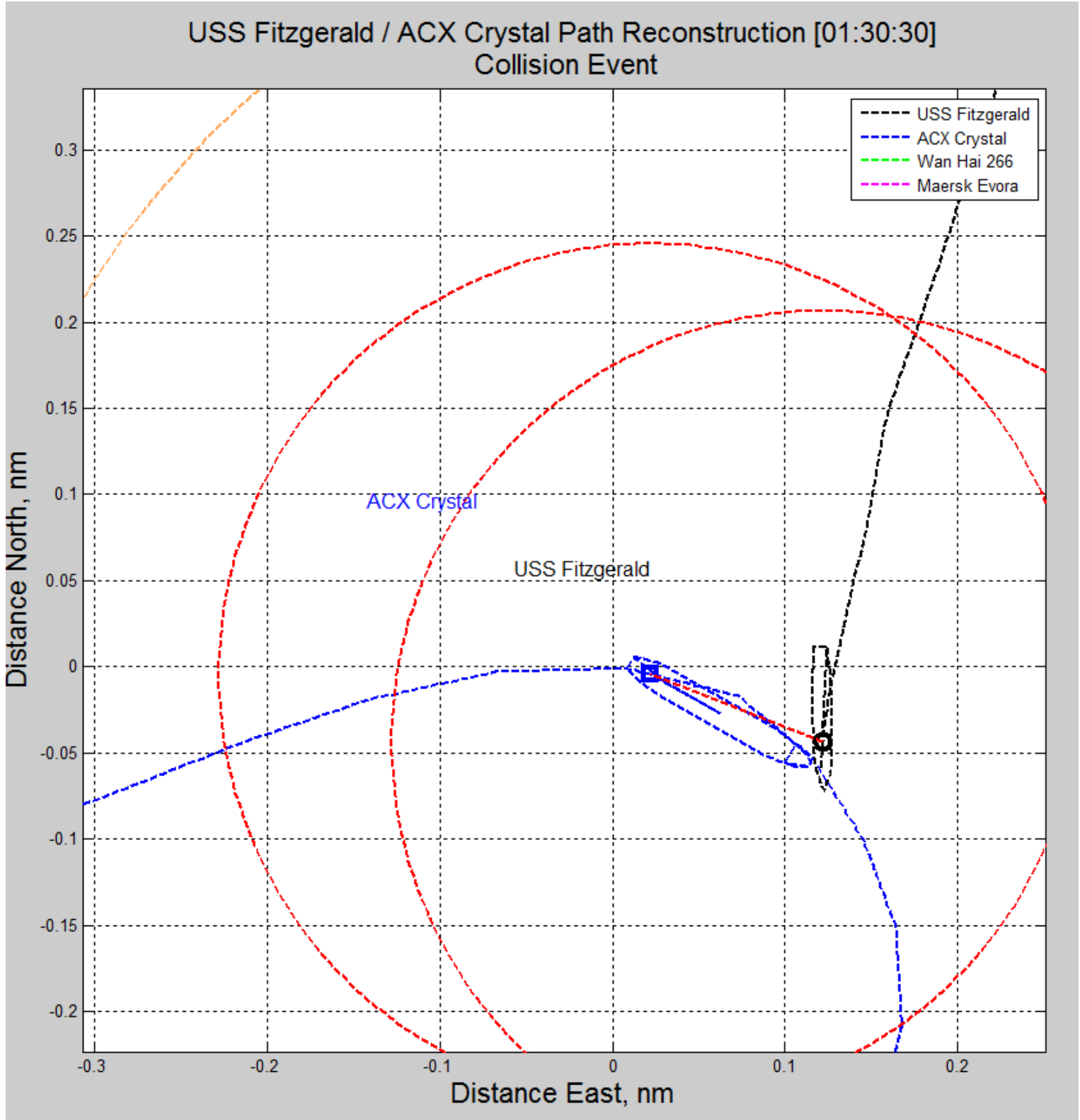
Figure A1.5: 01:28:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
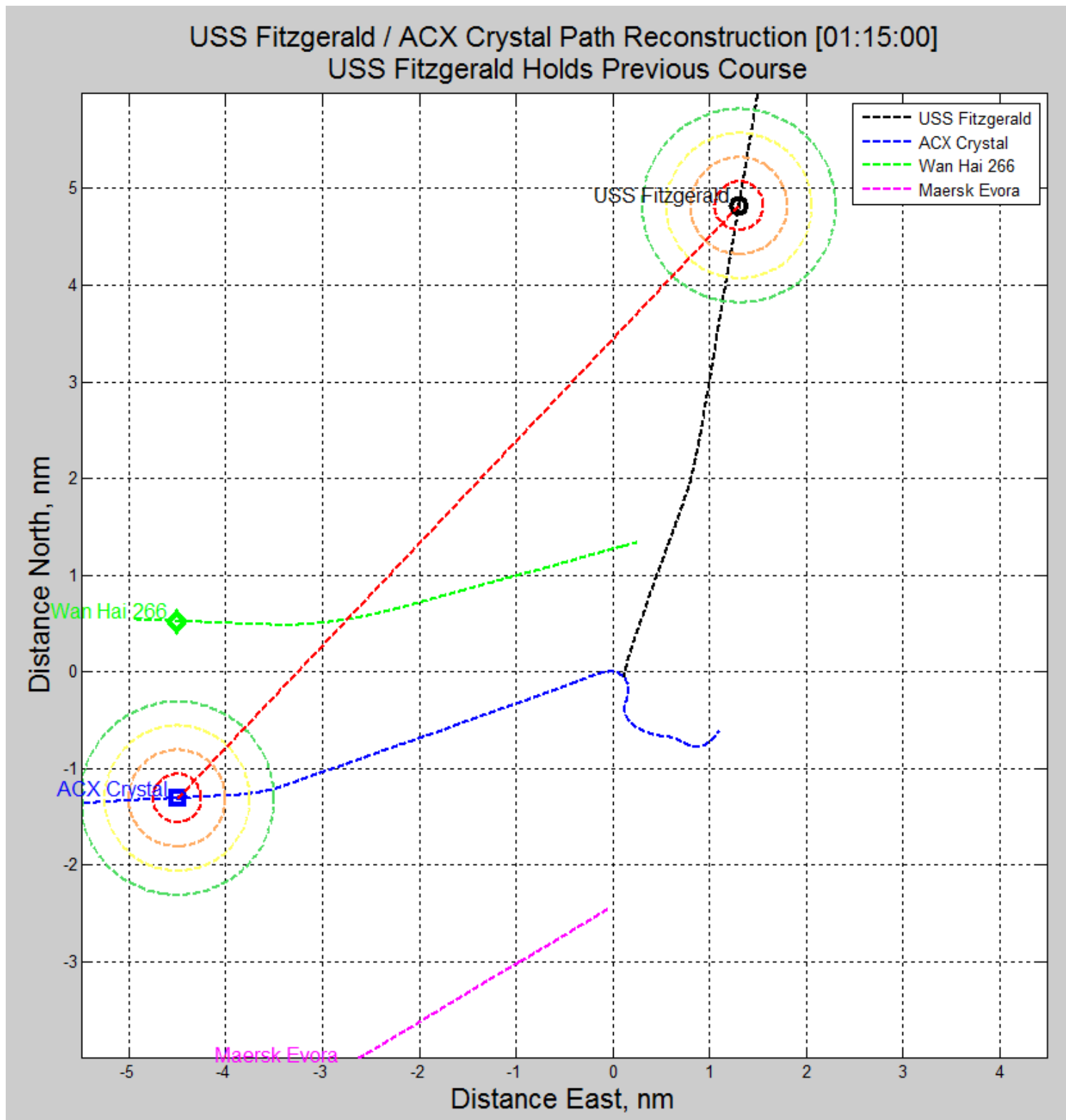
Figure A1.6: 01:29:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.

Figure A1.7: 01:30:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.
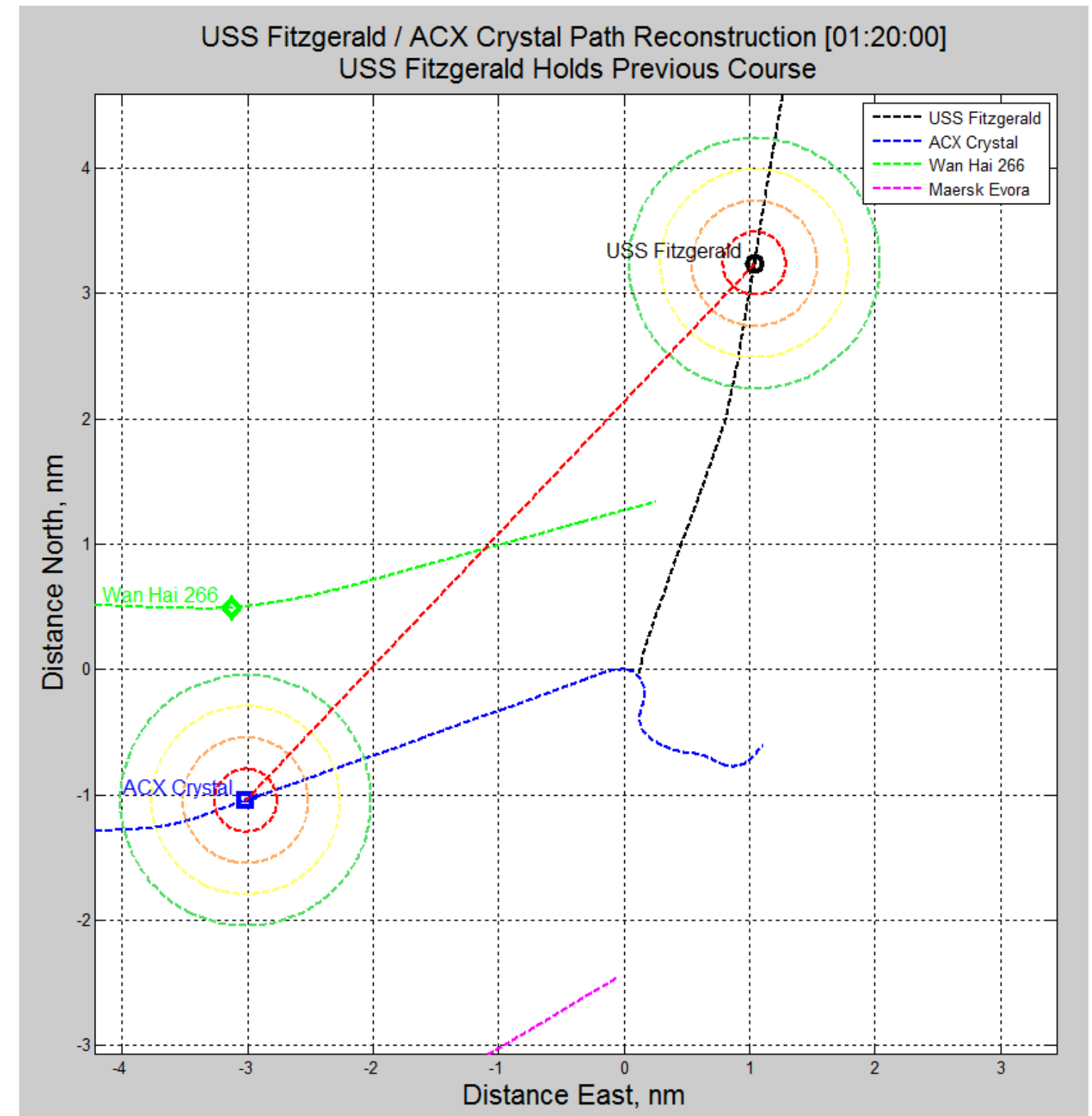
Figure A1.8: 01:30:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Event collision scenario based on recorded and reconstructed vessel position data.

Attachment 2

Alternate scenario vessel path reconstruction
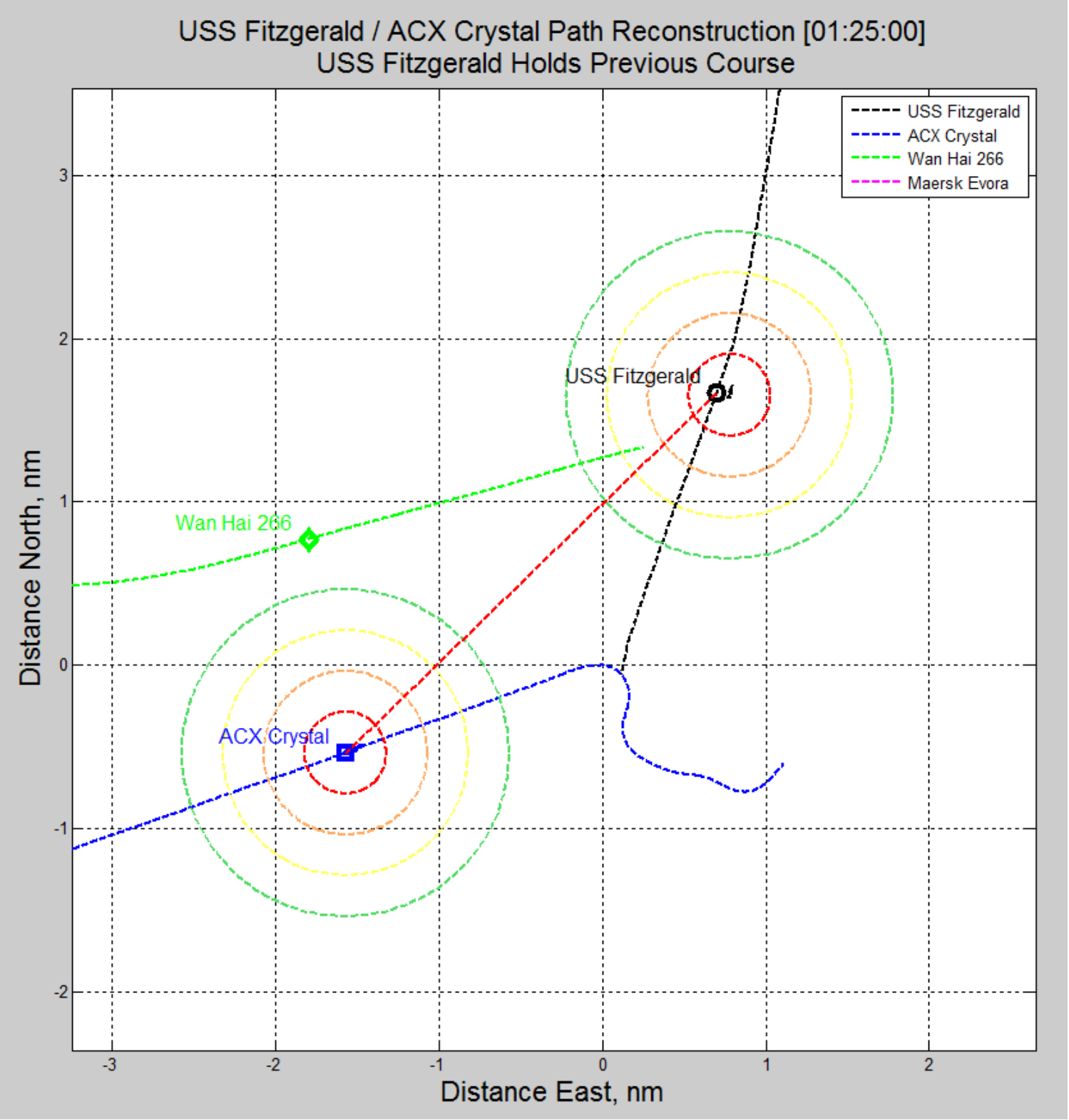(*USS Fitzgerald* omits its last recorded pre-collision course change)

Figure A2.1: 01:15:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
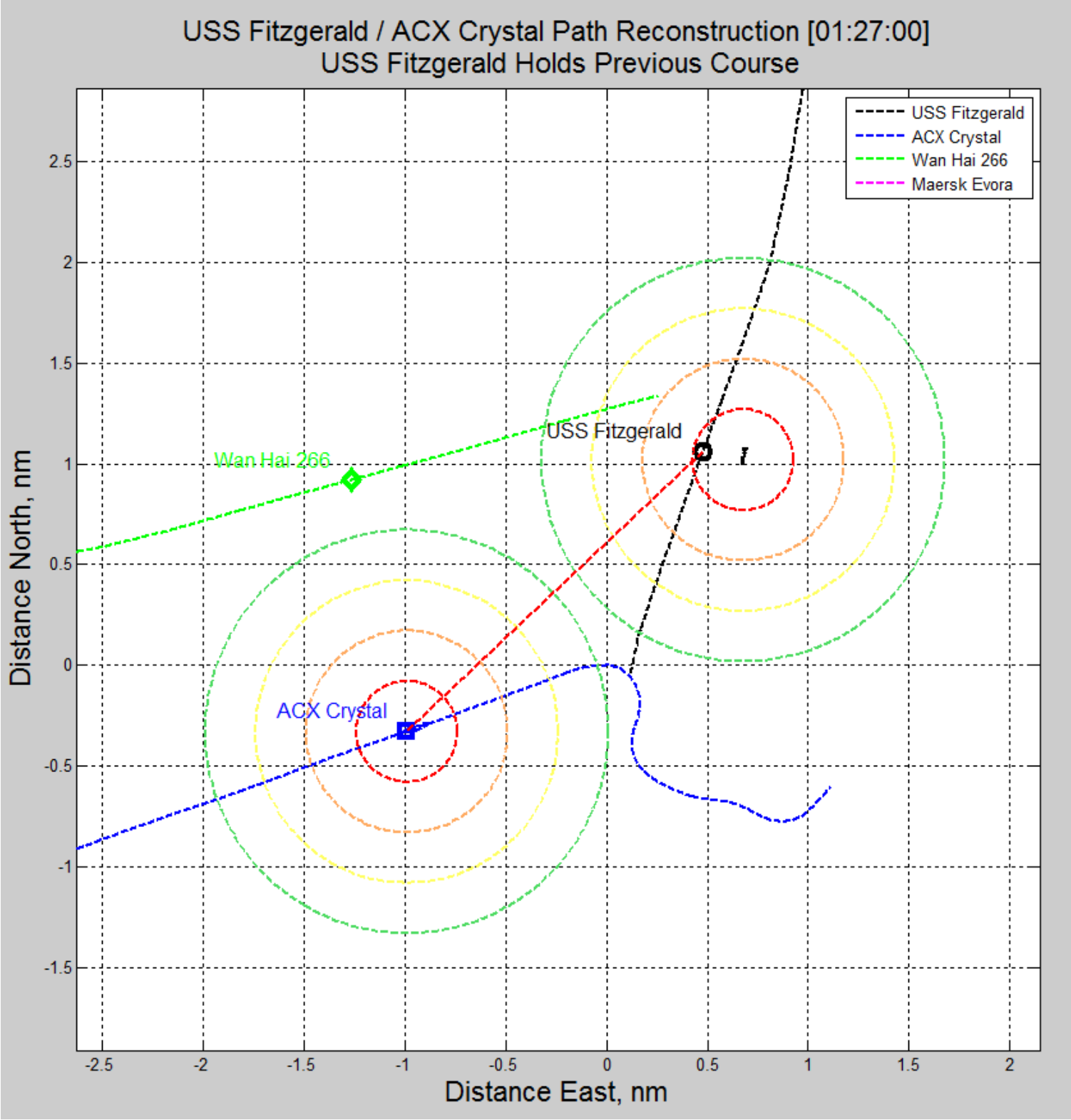
Figure A2.2: 01:20:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
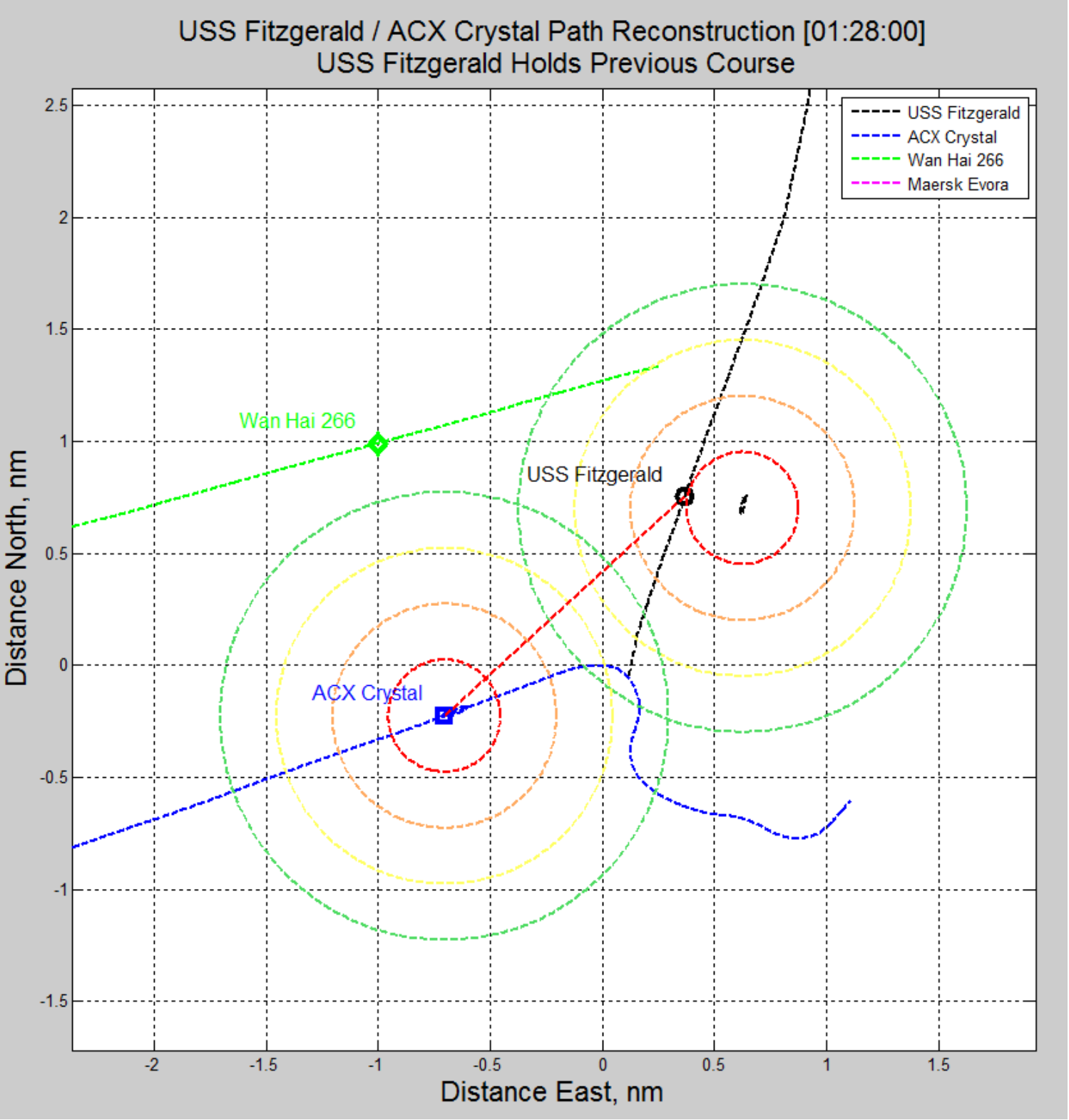
A2.2

Figure A2.3: 01:25:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
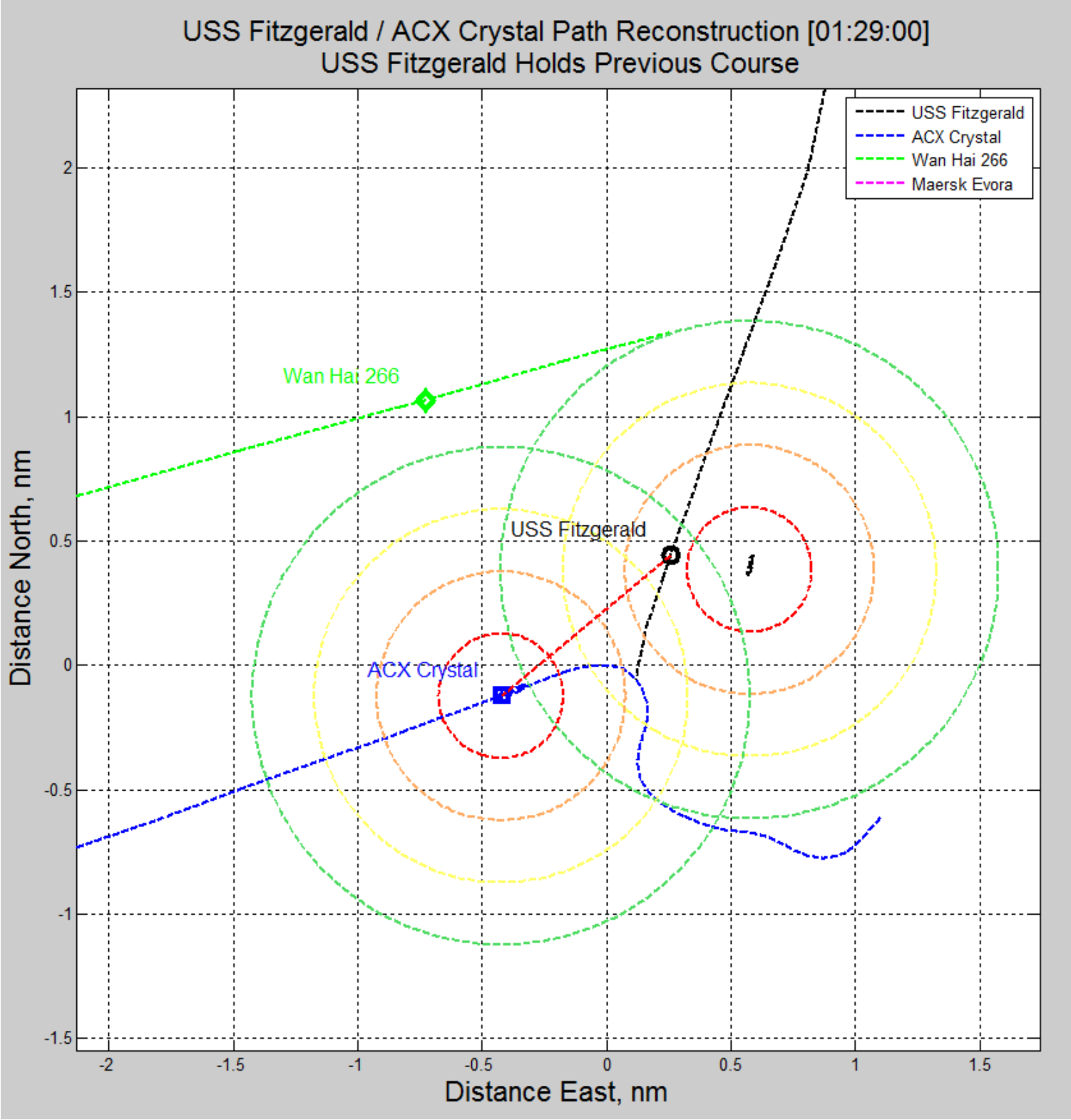
Figure A2.4: 01:27:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
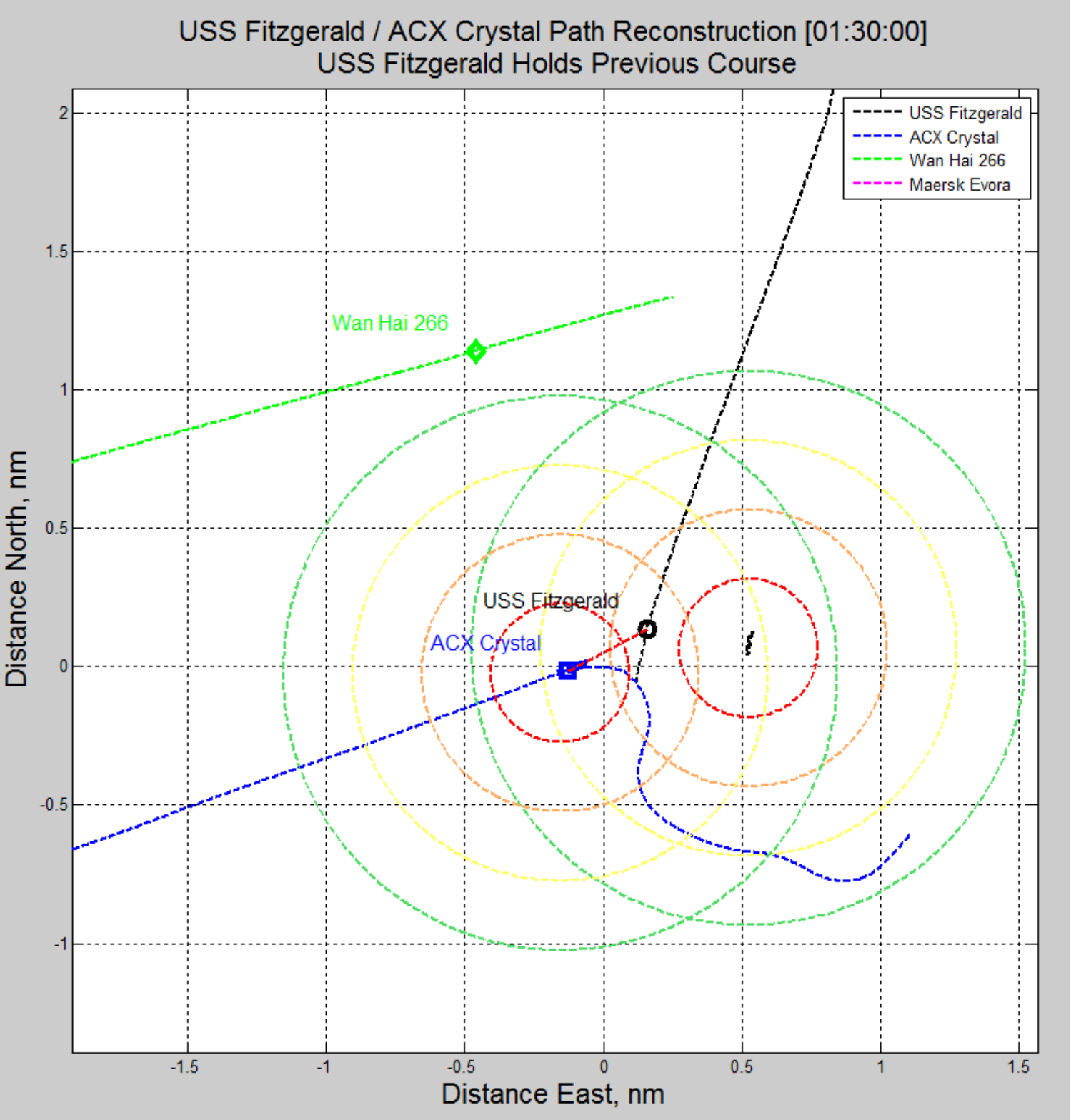
Figure A2.5: 01:28:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
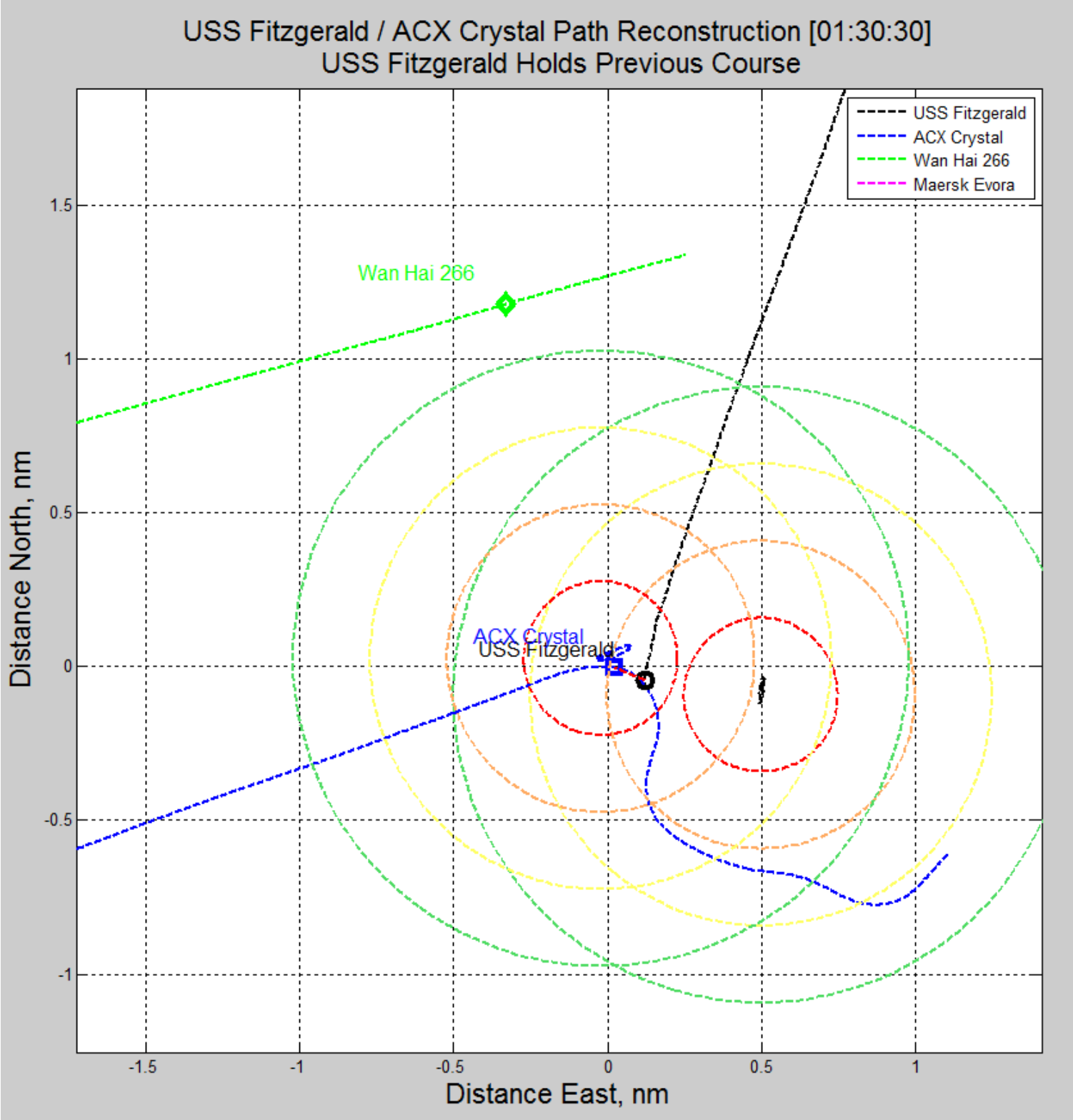
Figure A2.6: 01:29:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
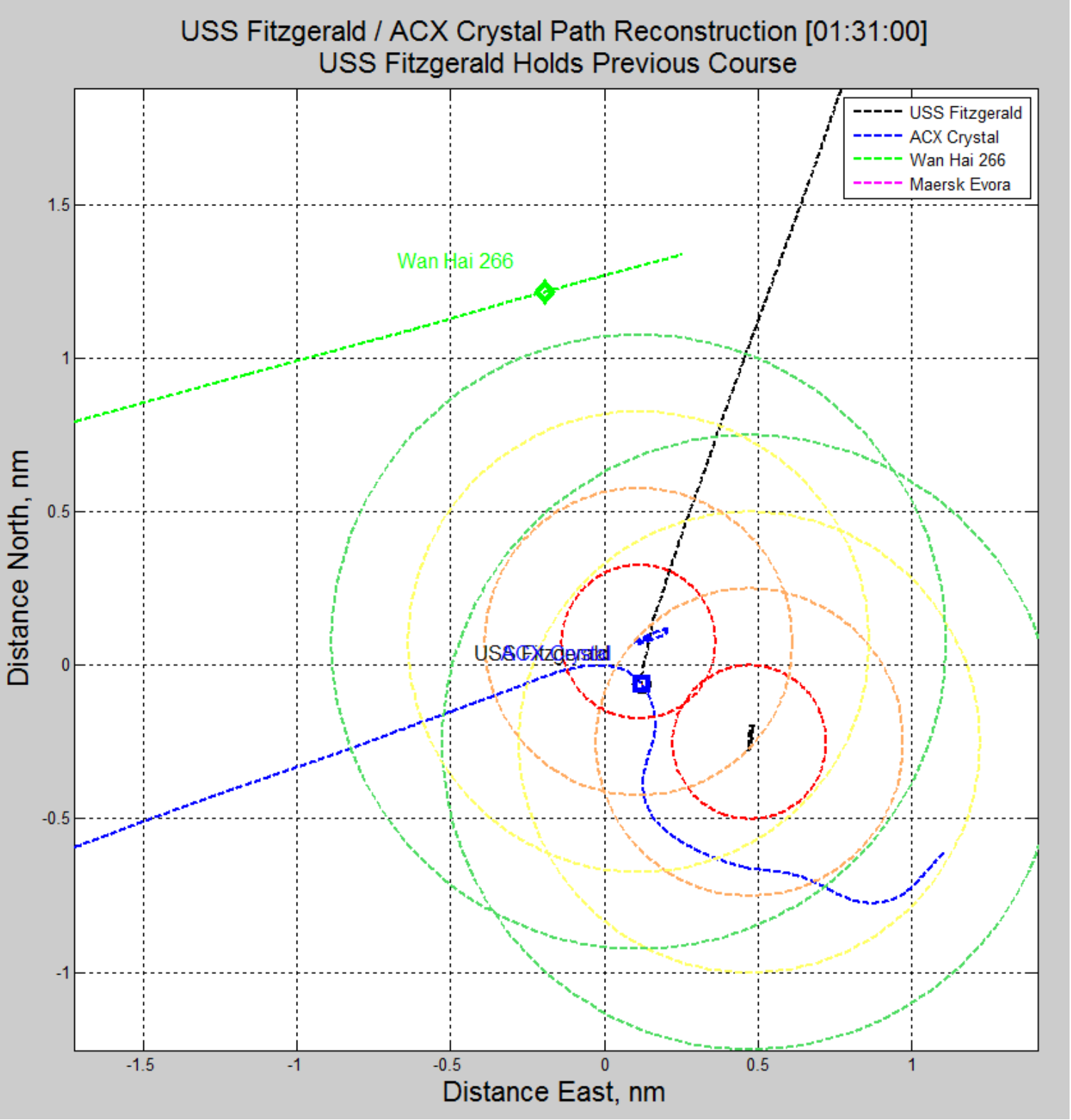
Figure A2.7: 01:30:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.
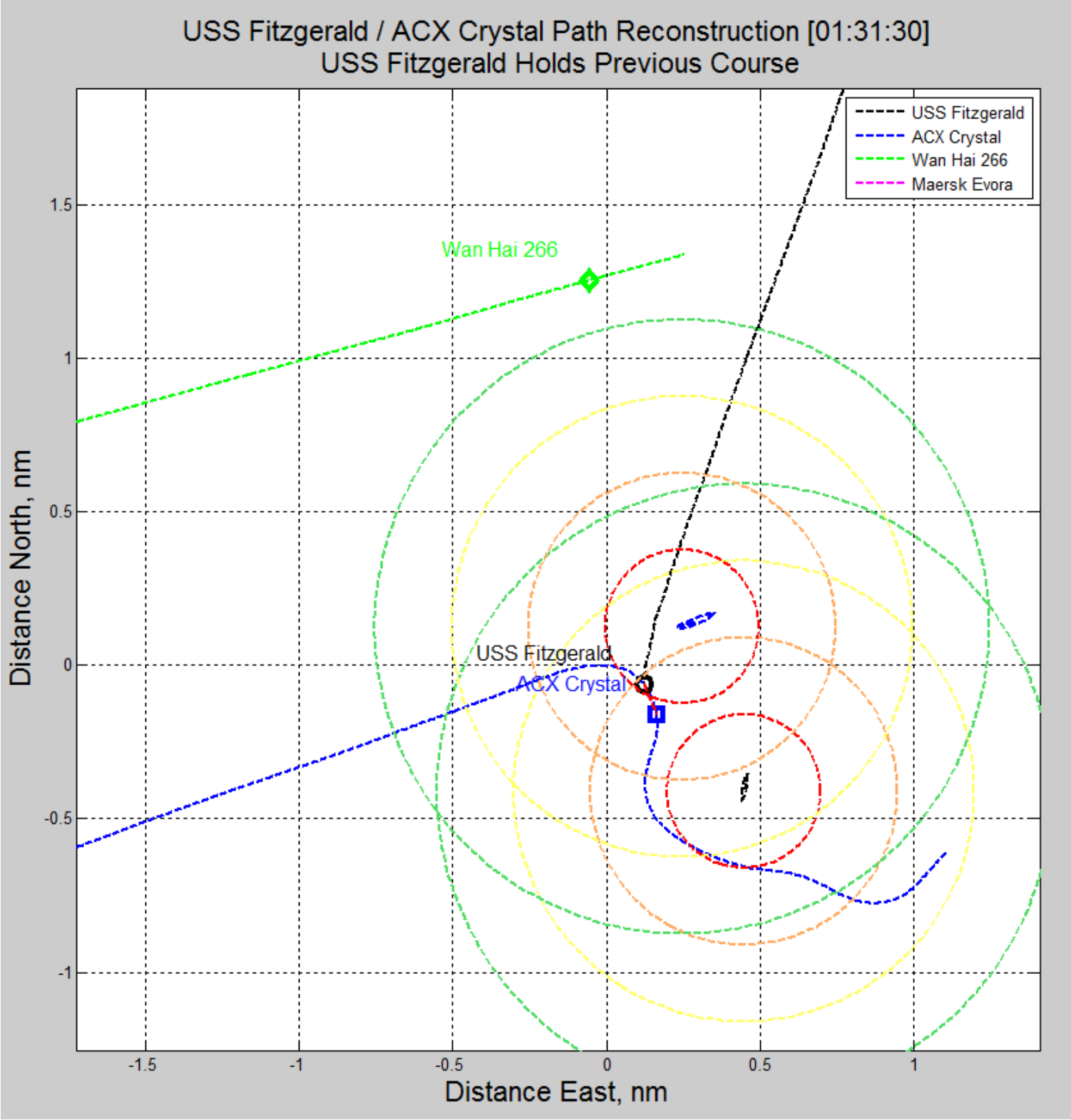
Figure A2.8: 01:30:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.

Figure A2.9: 01:31:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.

Figure A2.10: 01:31:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes *USS Fitzgerald* omits its last recorded pre-collision course change.

Attachment 3

Alternate scenario vessel path reconstruction
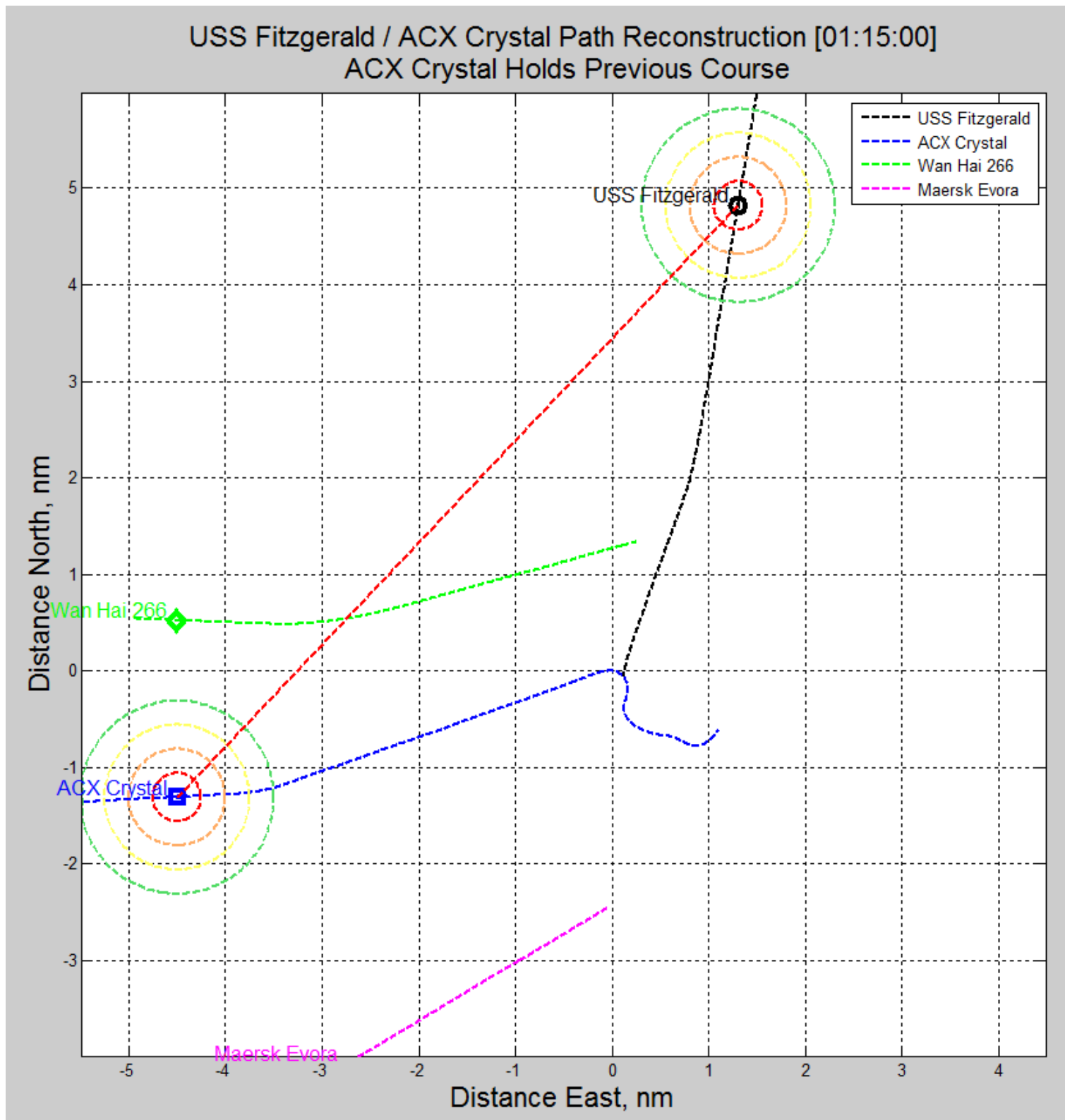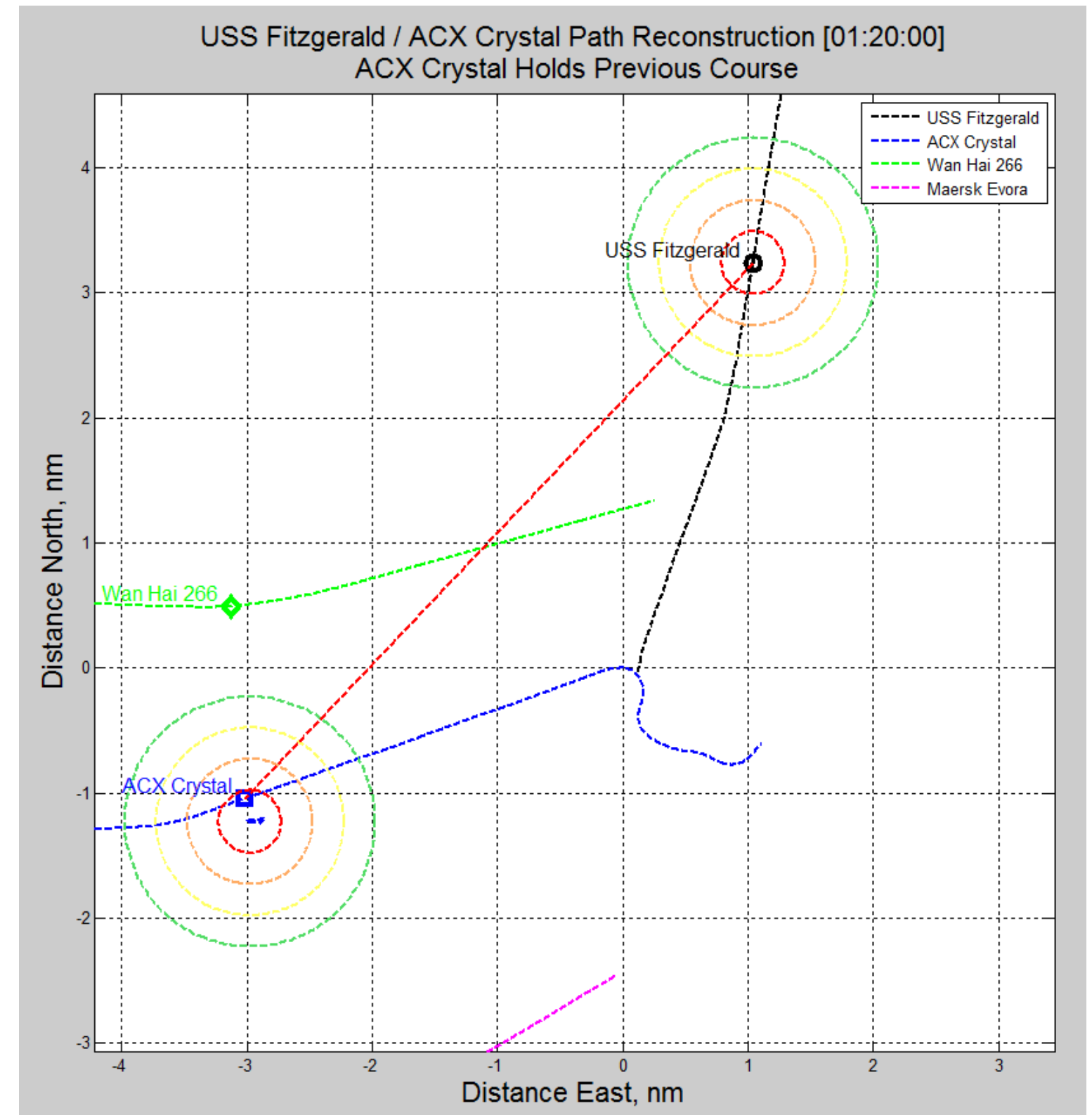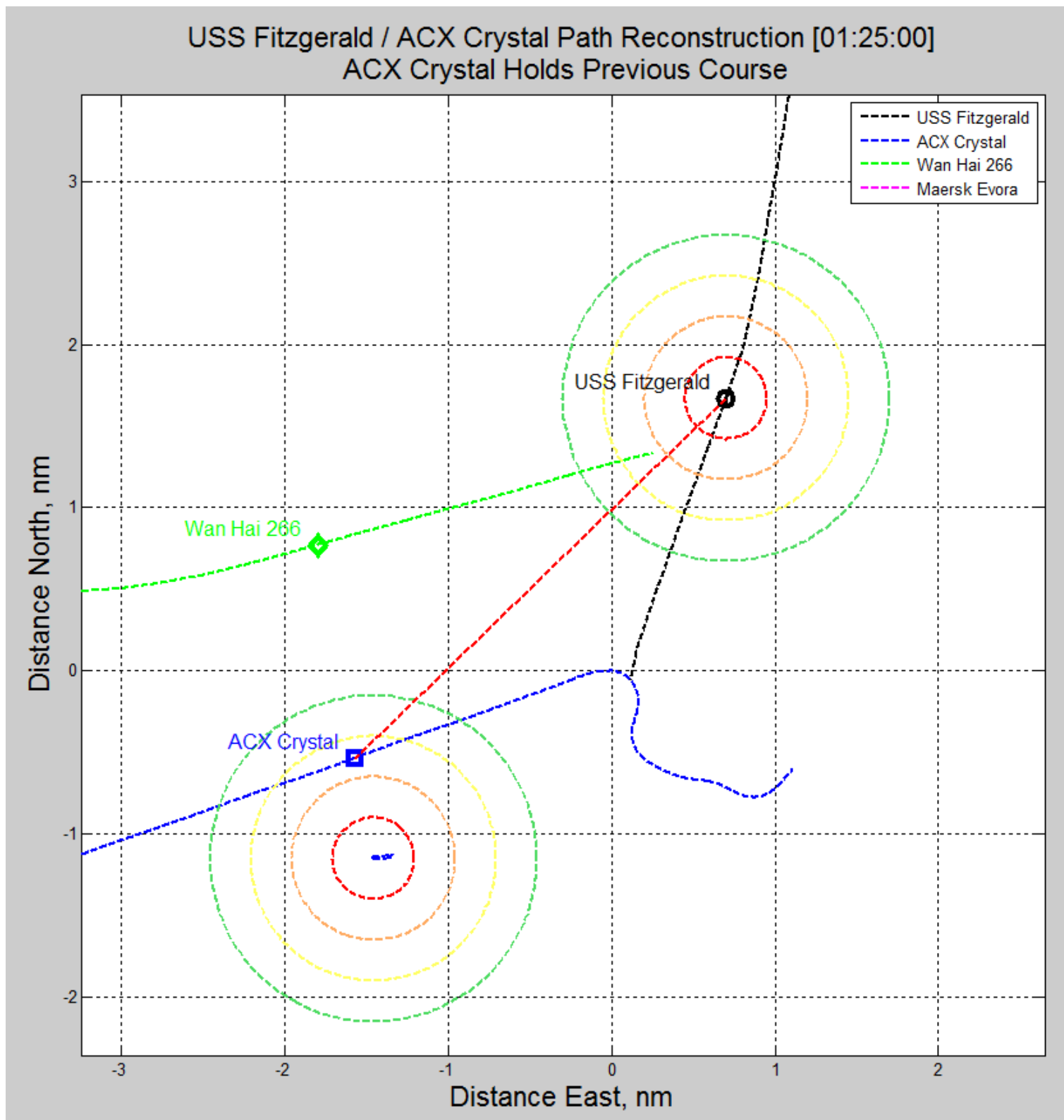(MV *ACX Crystal* omits its last recorded pre-collision course change)

Figure A3.1: 01:15:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
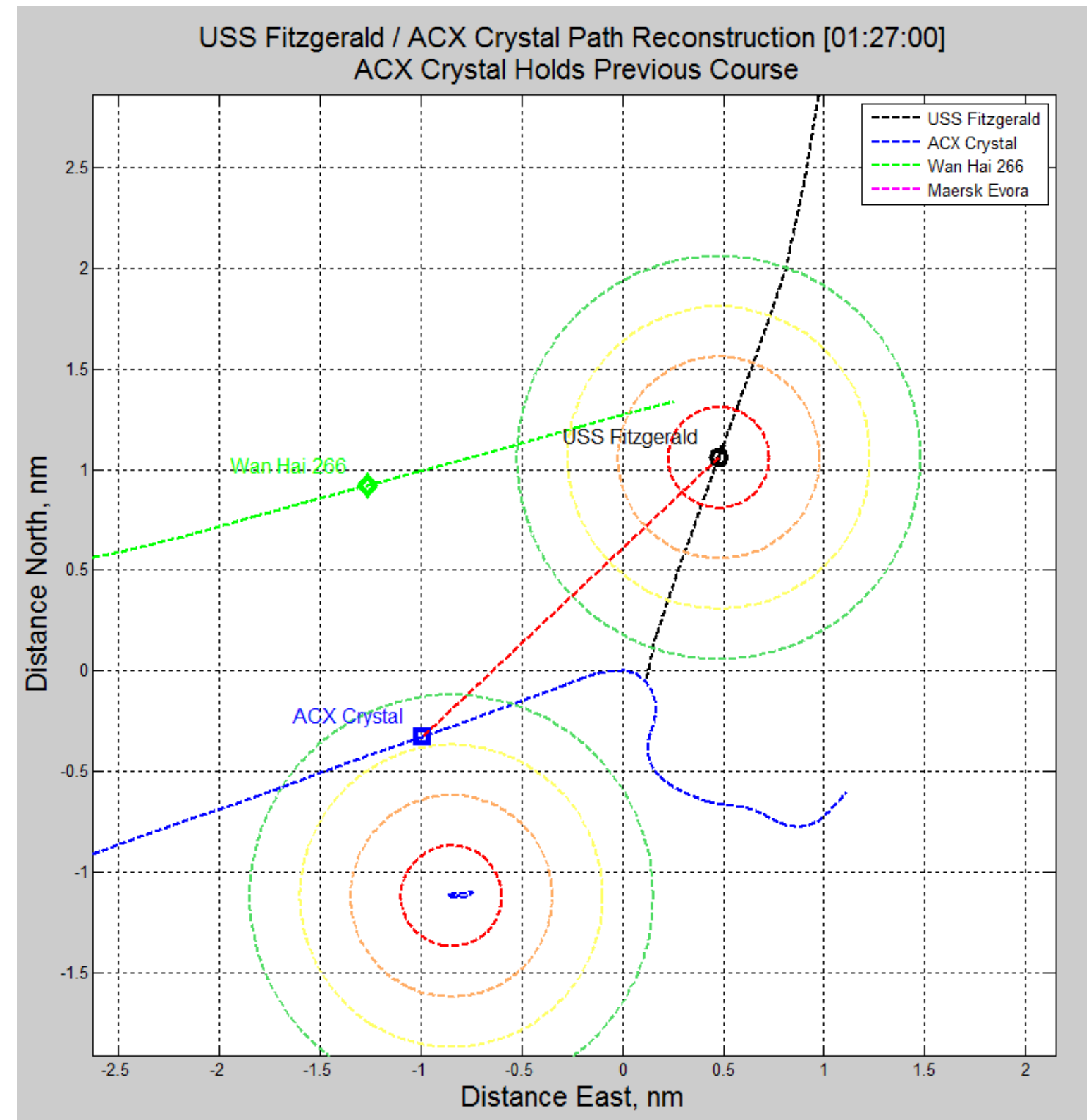
Figure A3.2: 01:20:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.

A3.2

Figure A3.3: 01:25:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
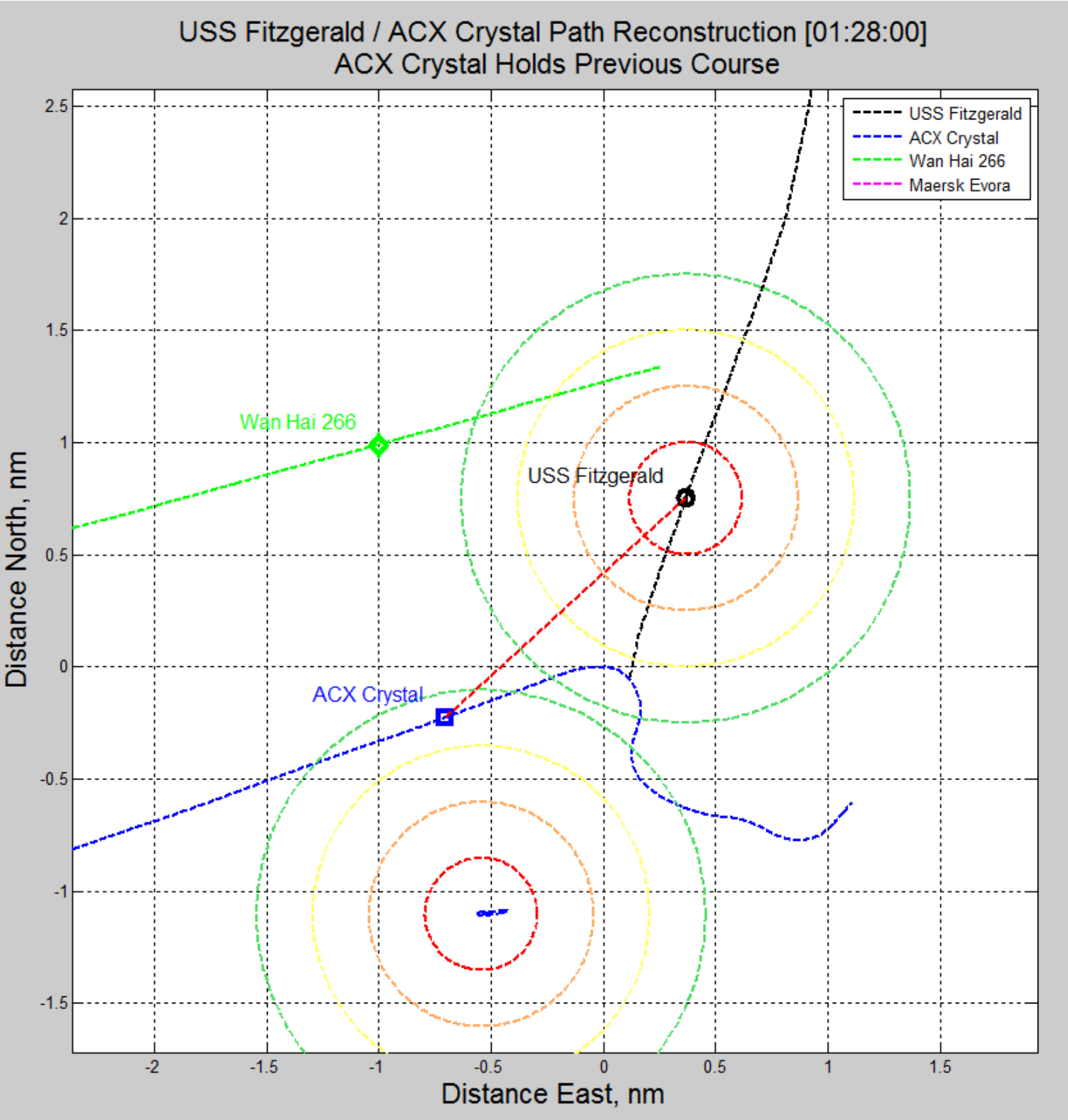
Figure A3.4: 01:27:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
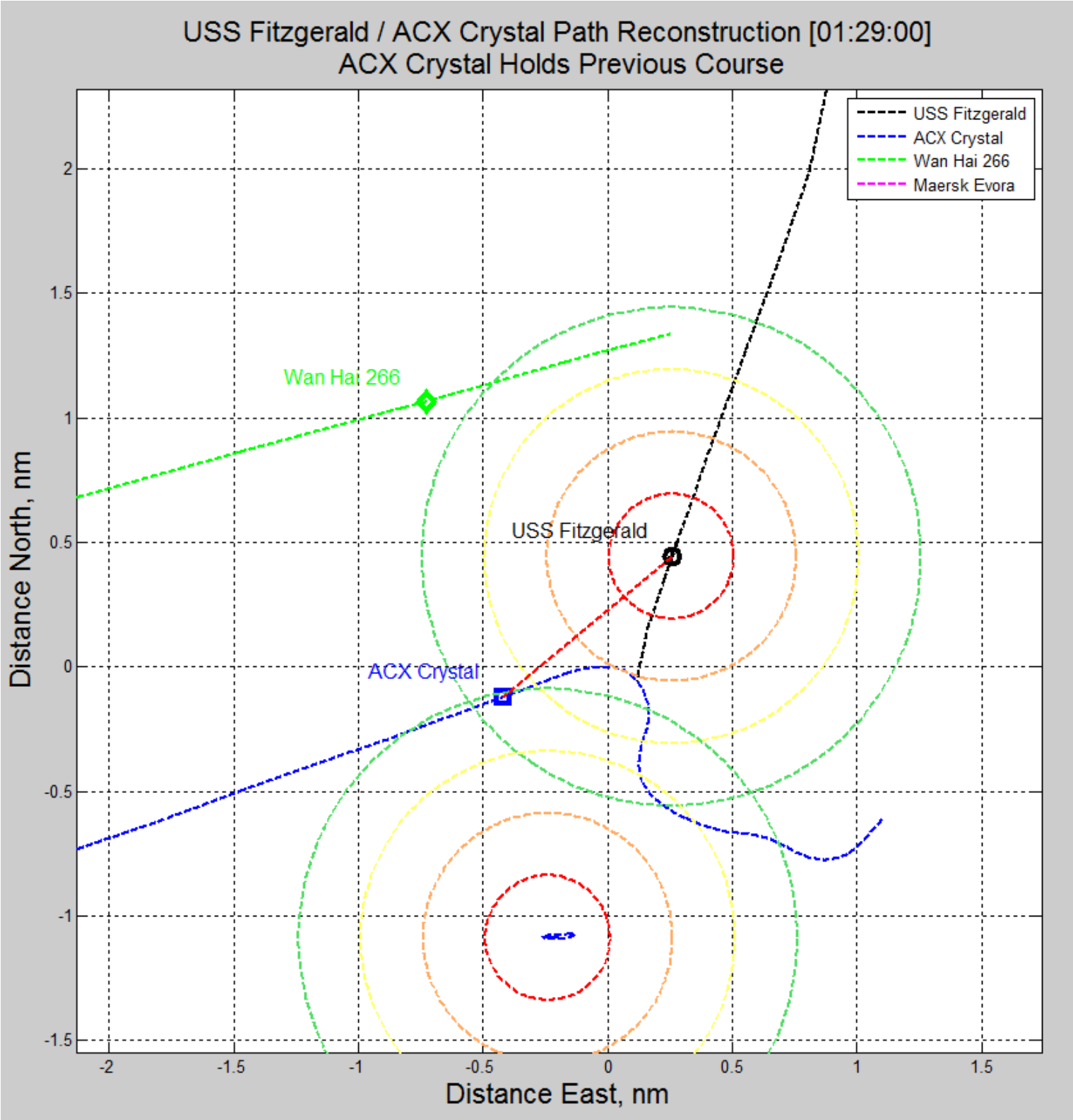
Figure A3.5: 01:28:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
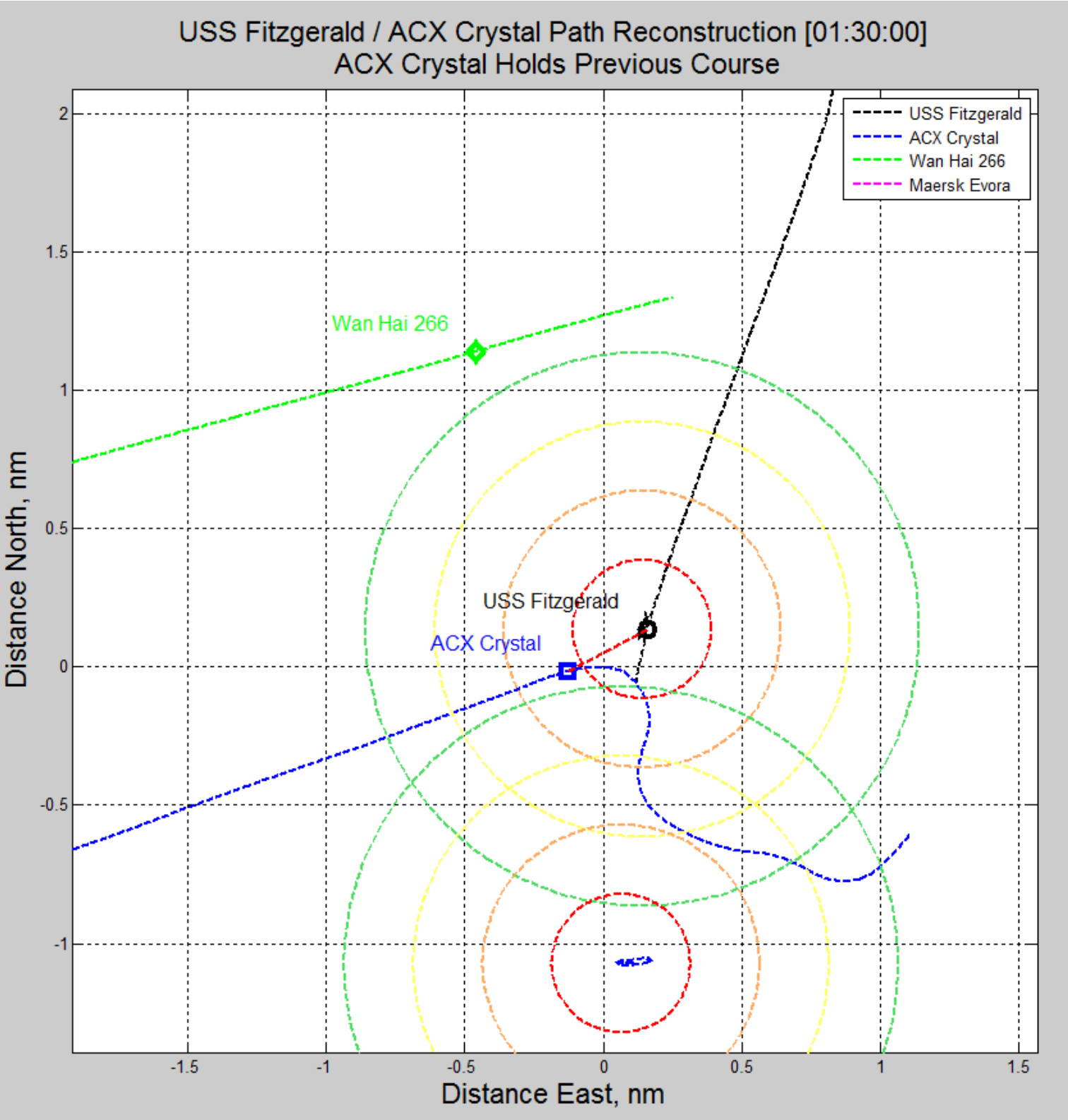
Figure A3.6: 01:29:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
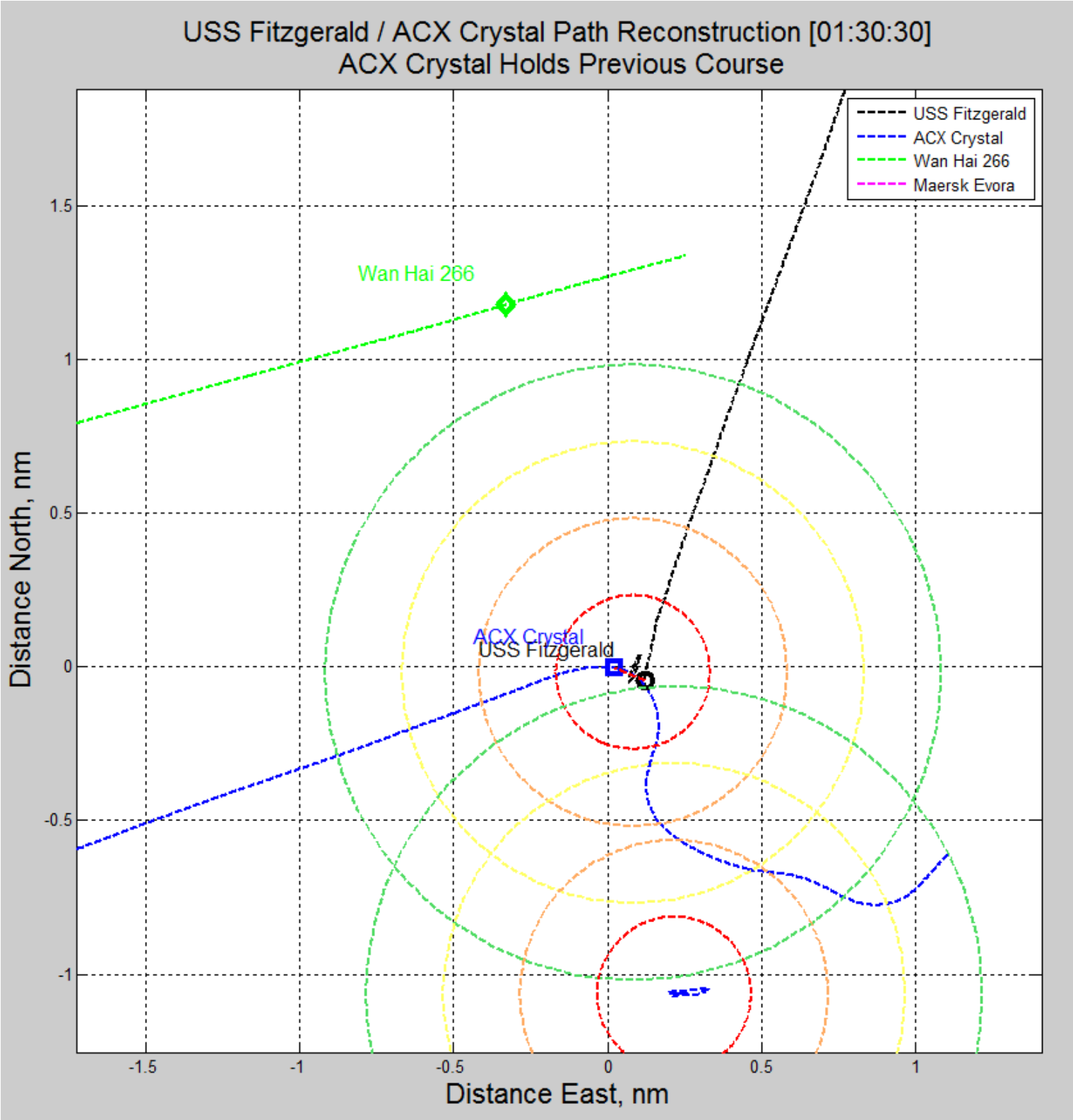
Figure A3.7: 01:30:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
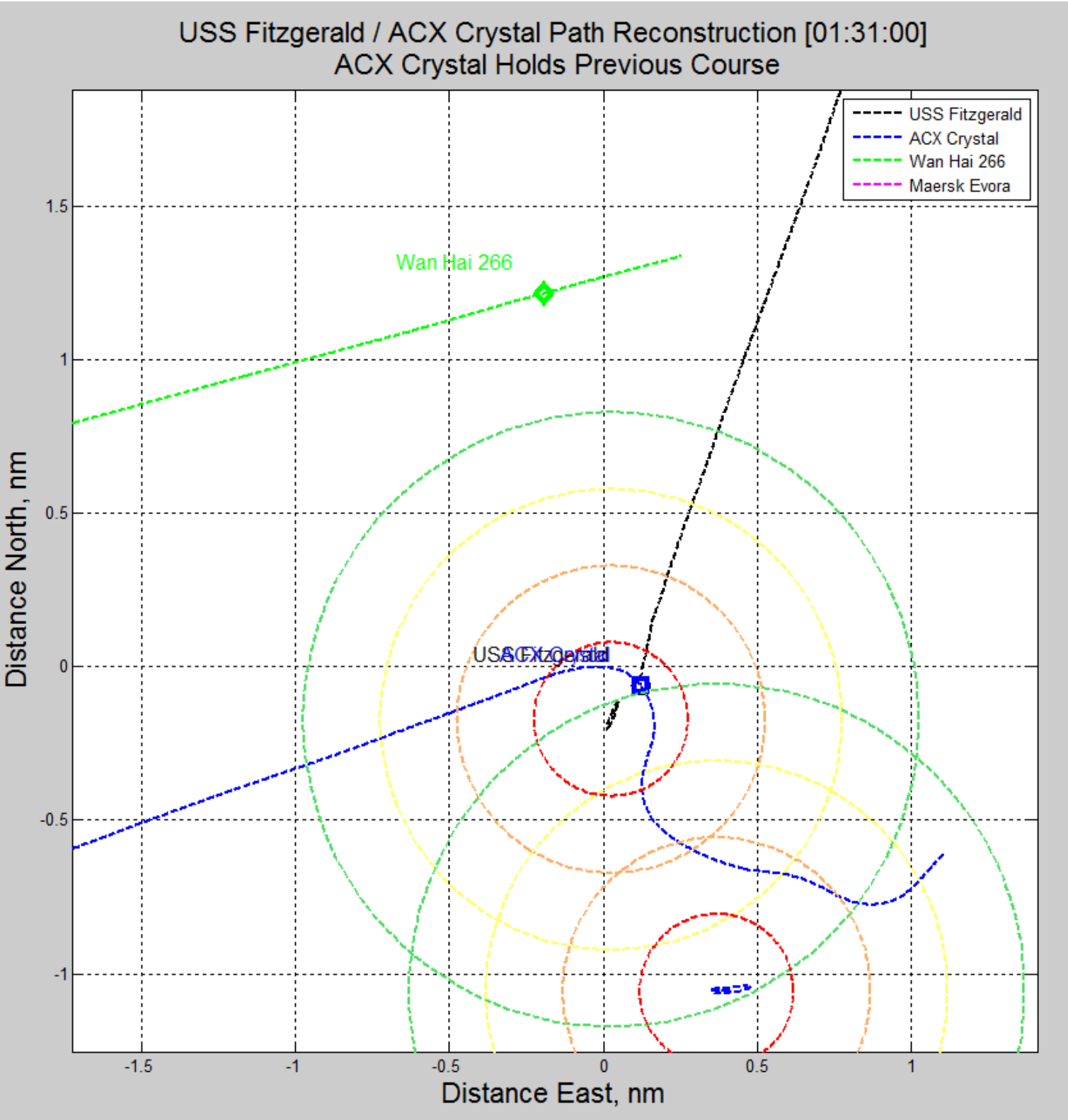
Figure A3.8: 01:30:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.
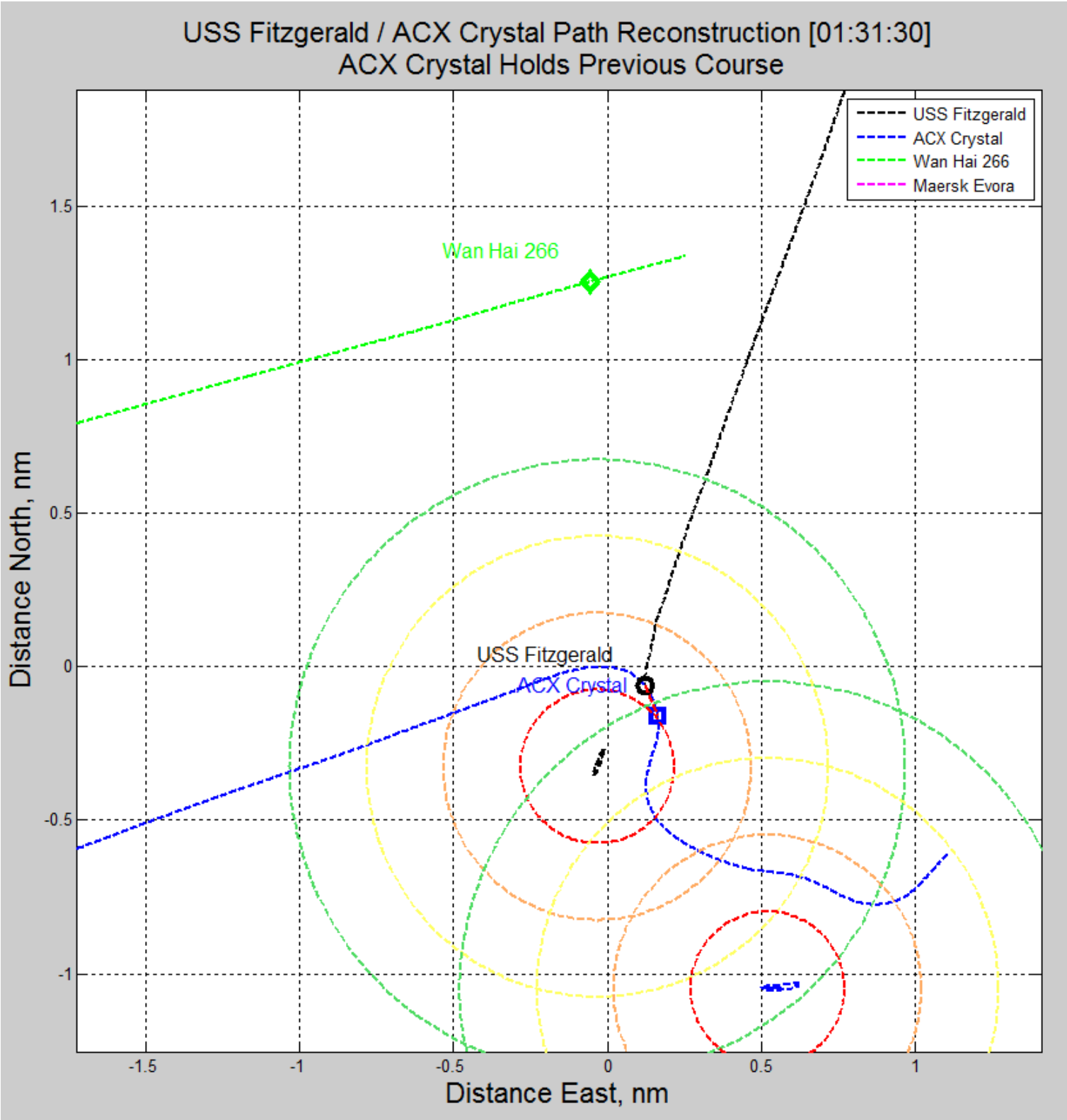
Figure A3.9: 01:31:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.

Figure A3.10: 01:31:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes MV *ACX Crystal* omits its last recorded pre-collision course change.

Attachment 4

Alternate scenario vessel path reconstruction
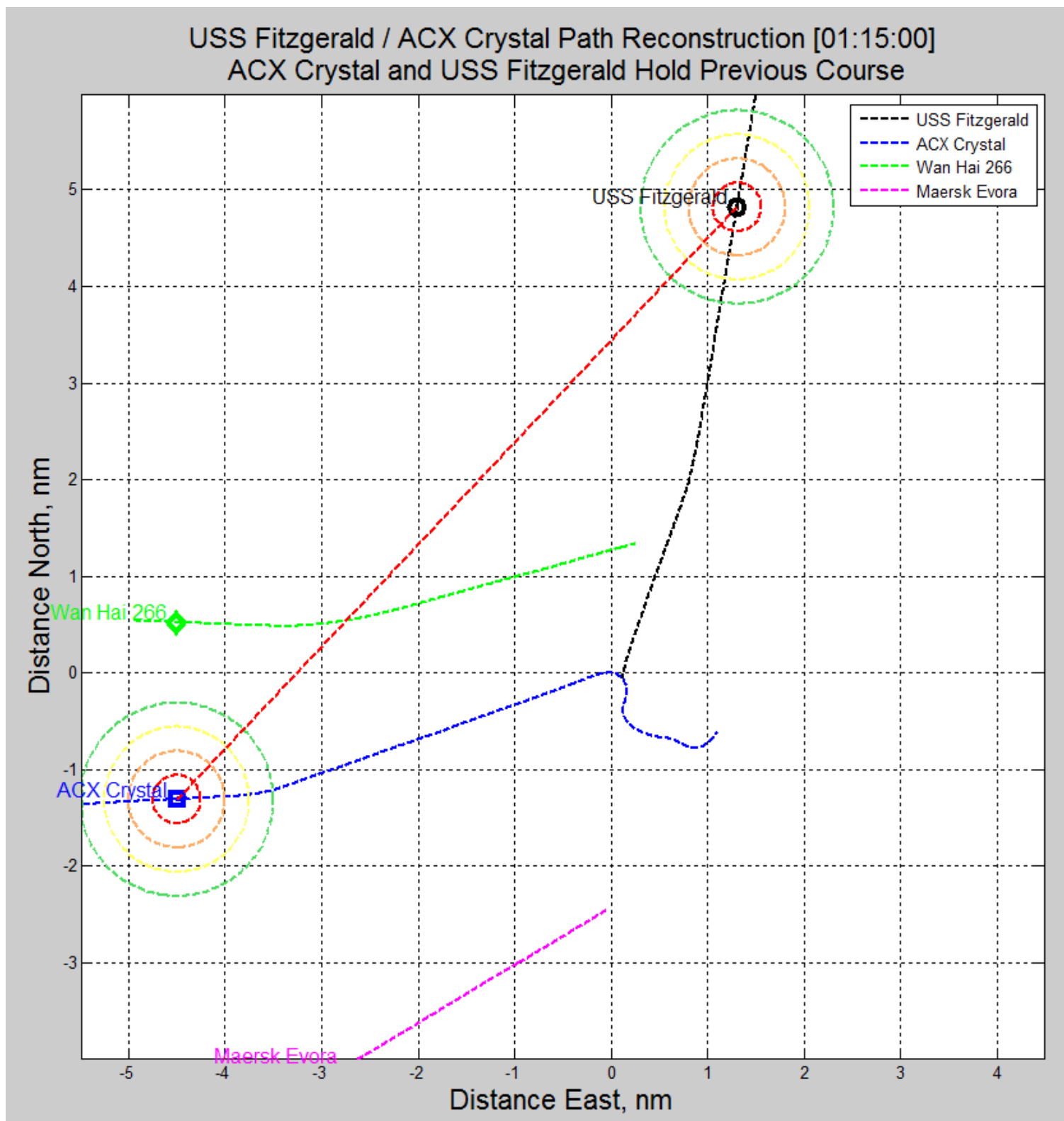(Each vessel omits its last recorded pre-collision course change)

Figure A4.1: 01:15:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
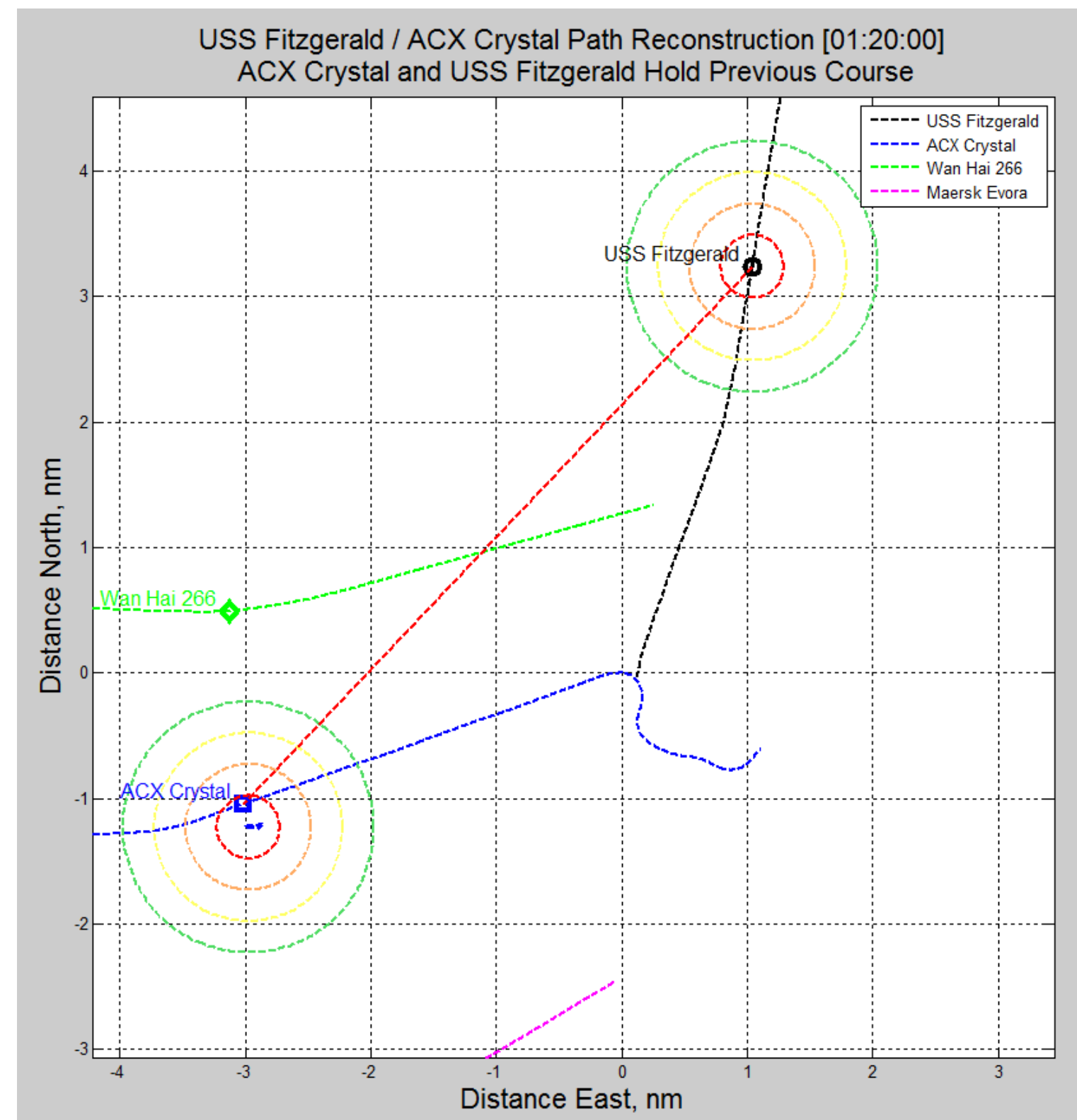
Figure A4.2: 01:20:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
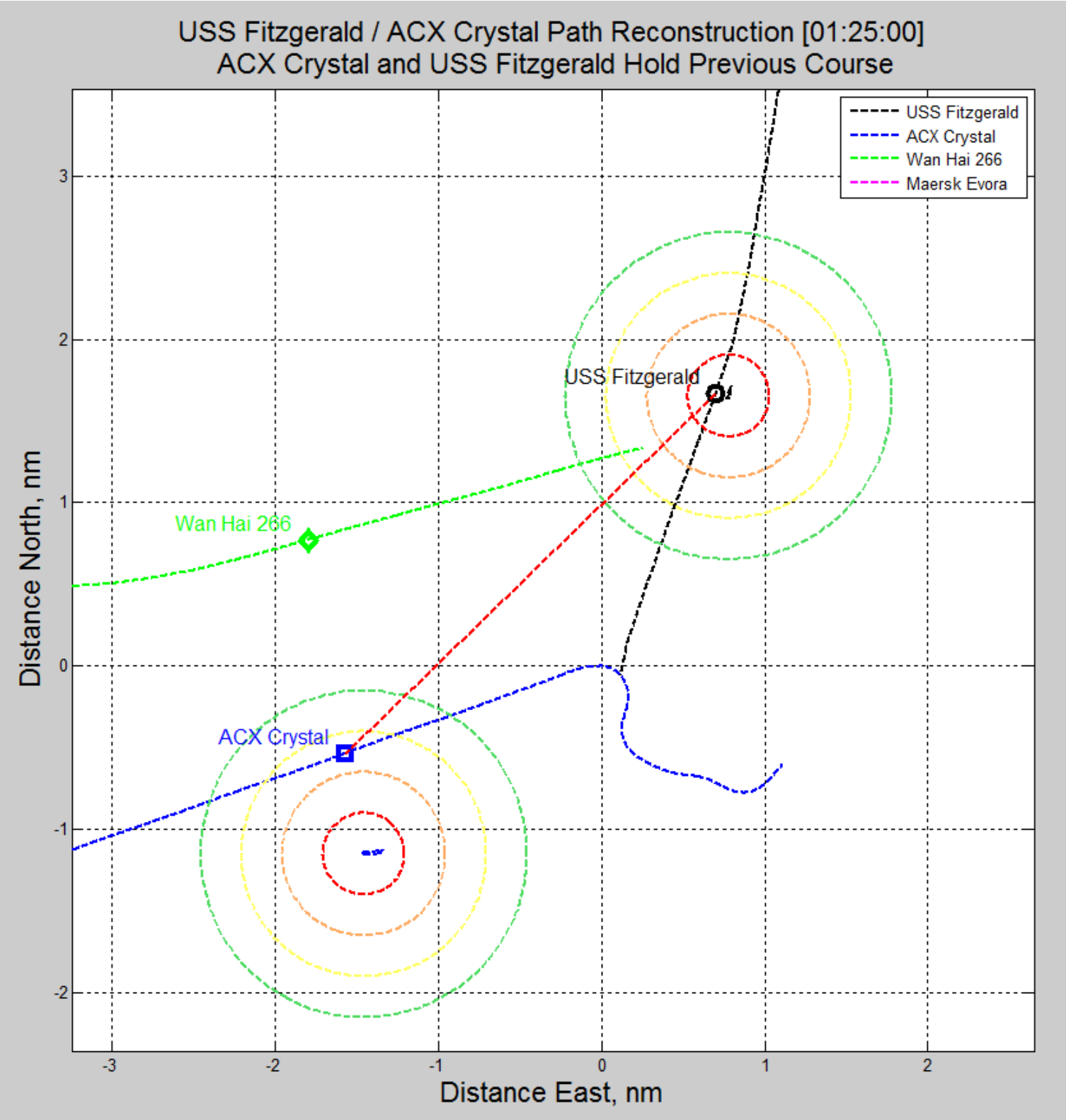
Figure A4.3: 01:25:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
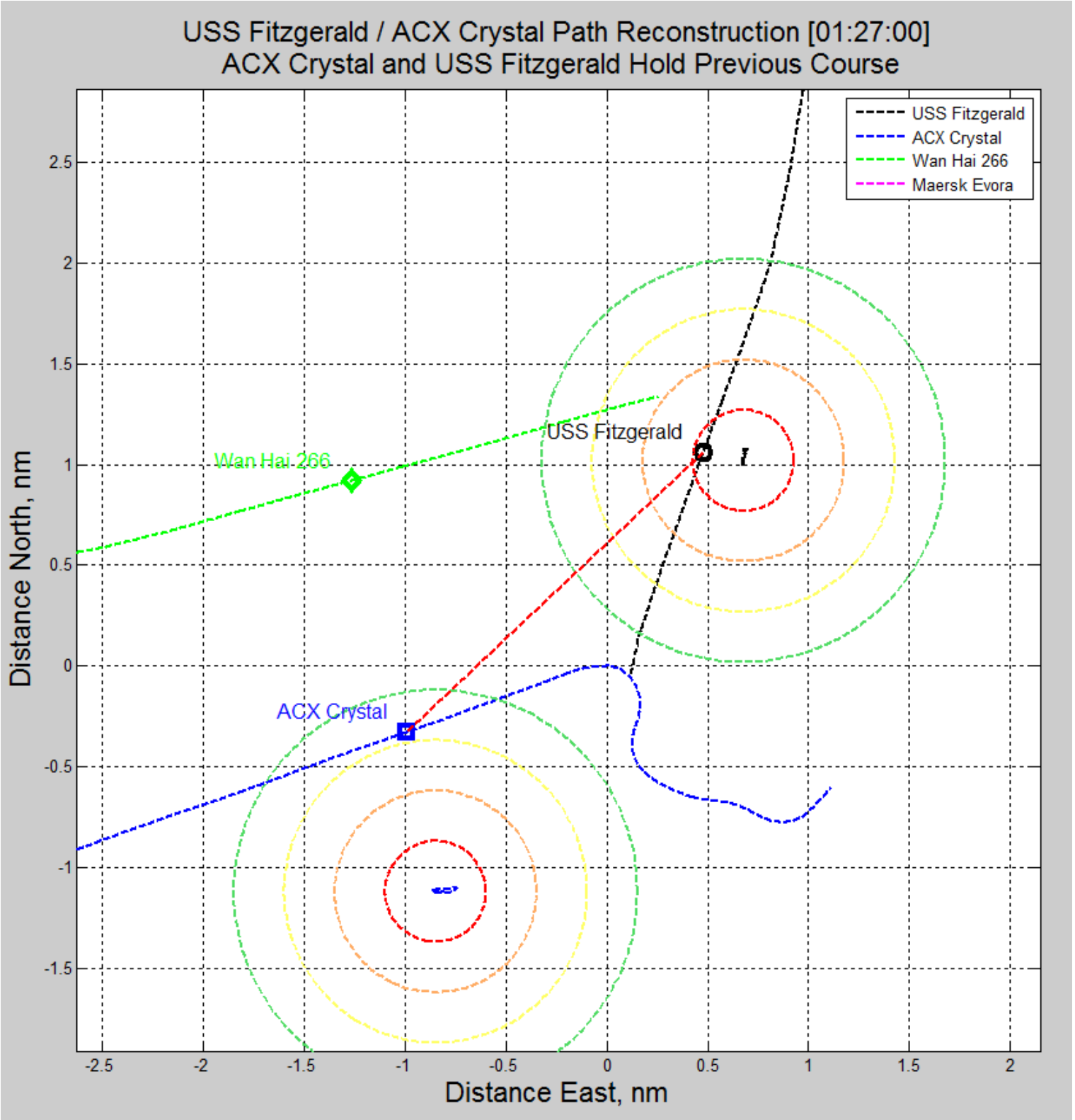
Figure A4.4: 01:27:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
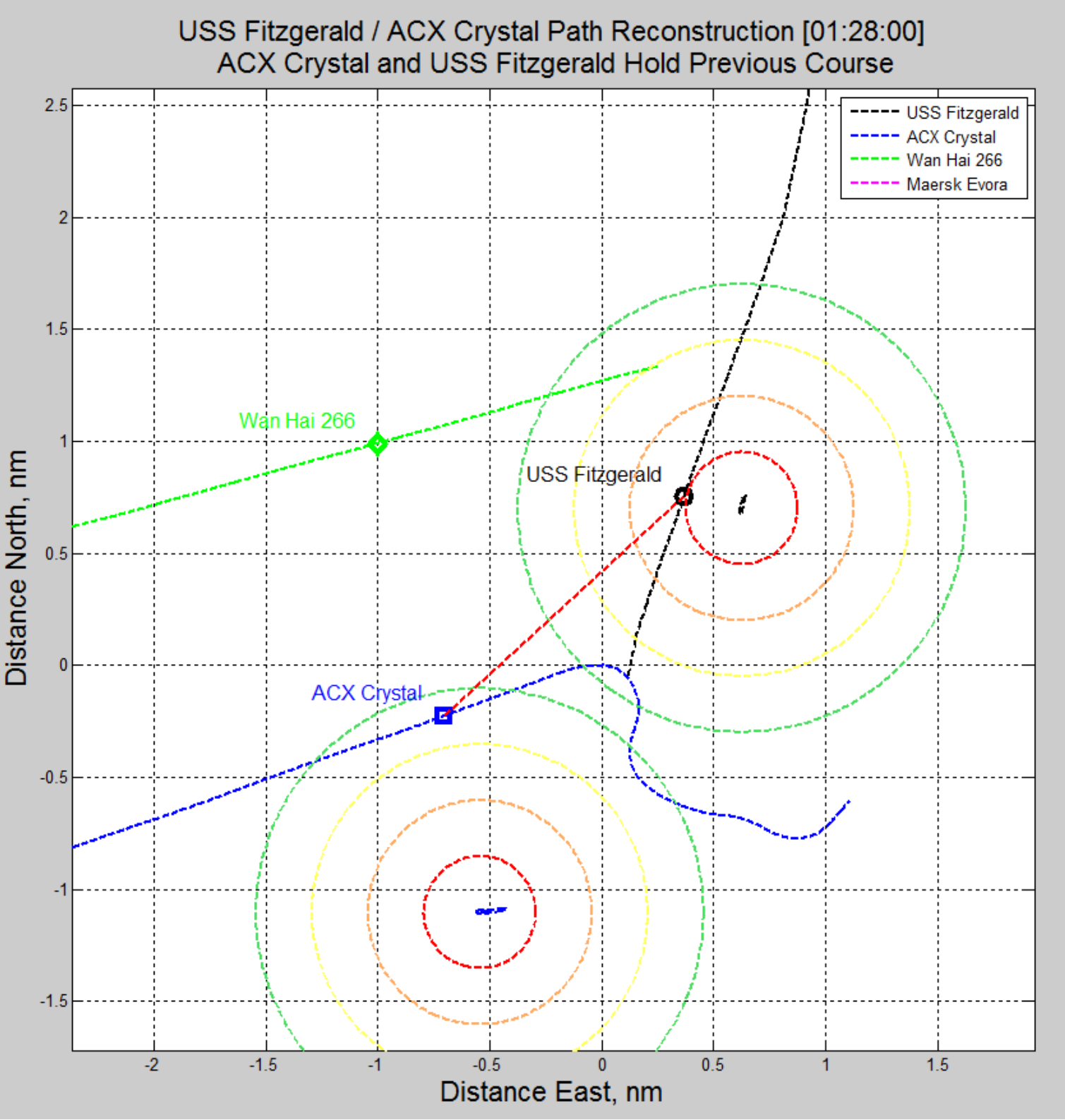
Figure A4.5: 01:28:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50. 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
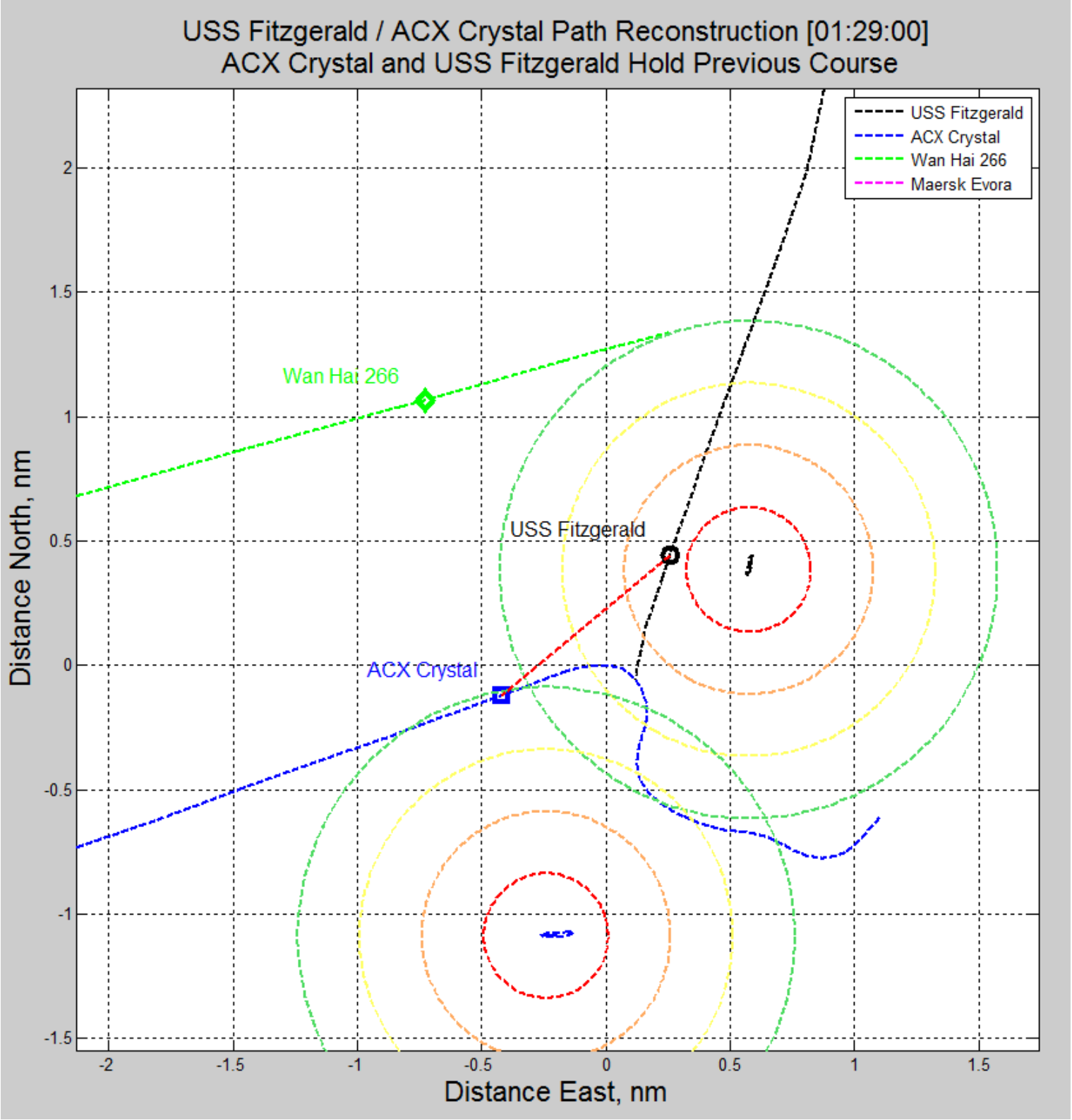
Figure A4.6: 01:29:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
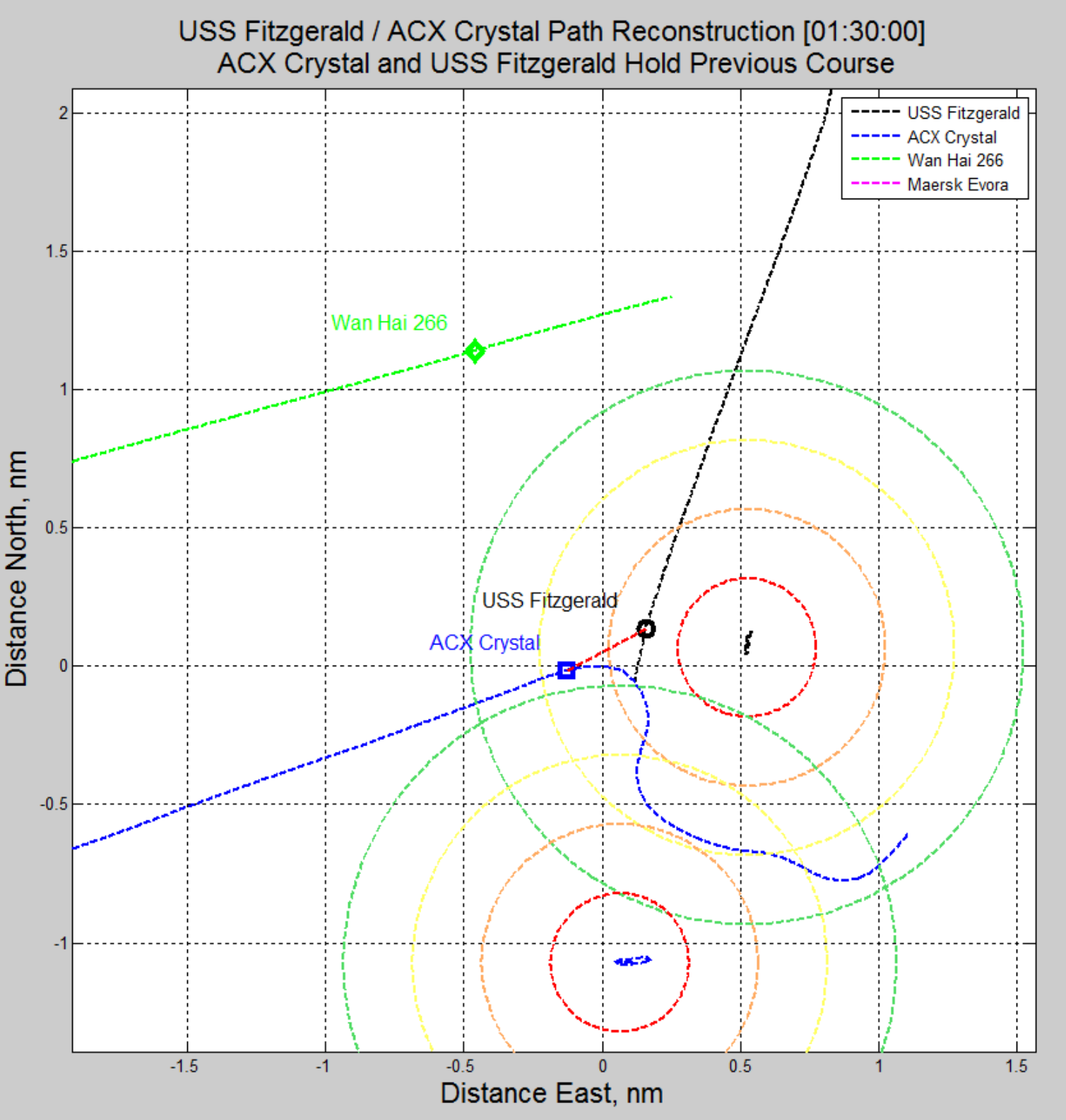
Figure A4.7: 01:30:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50. 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
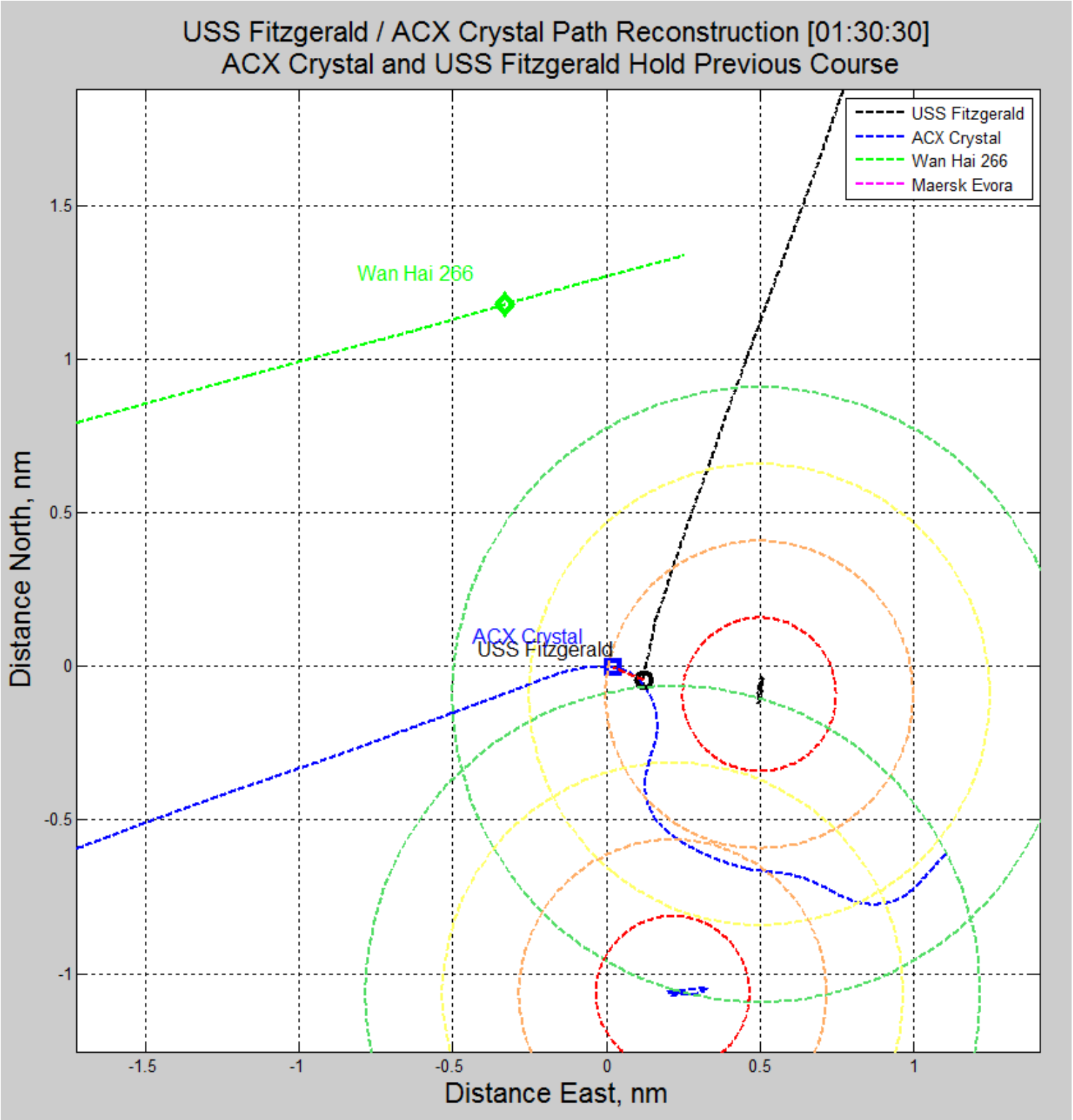

Figure A4.8: 01:30:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50. 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
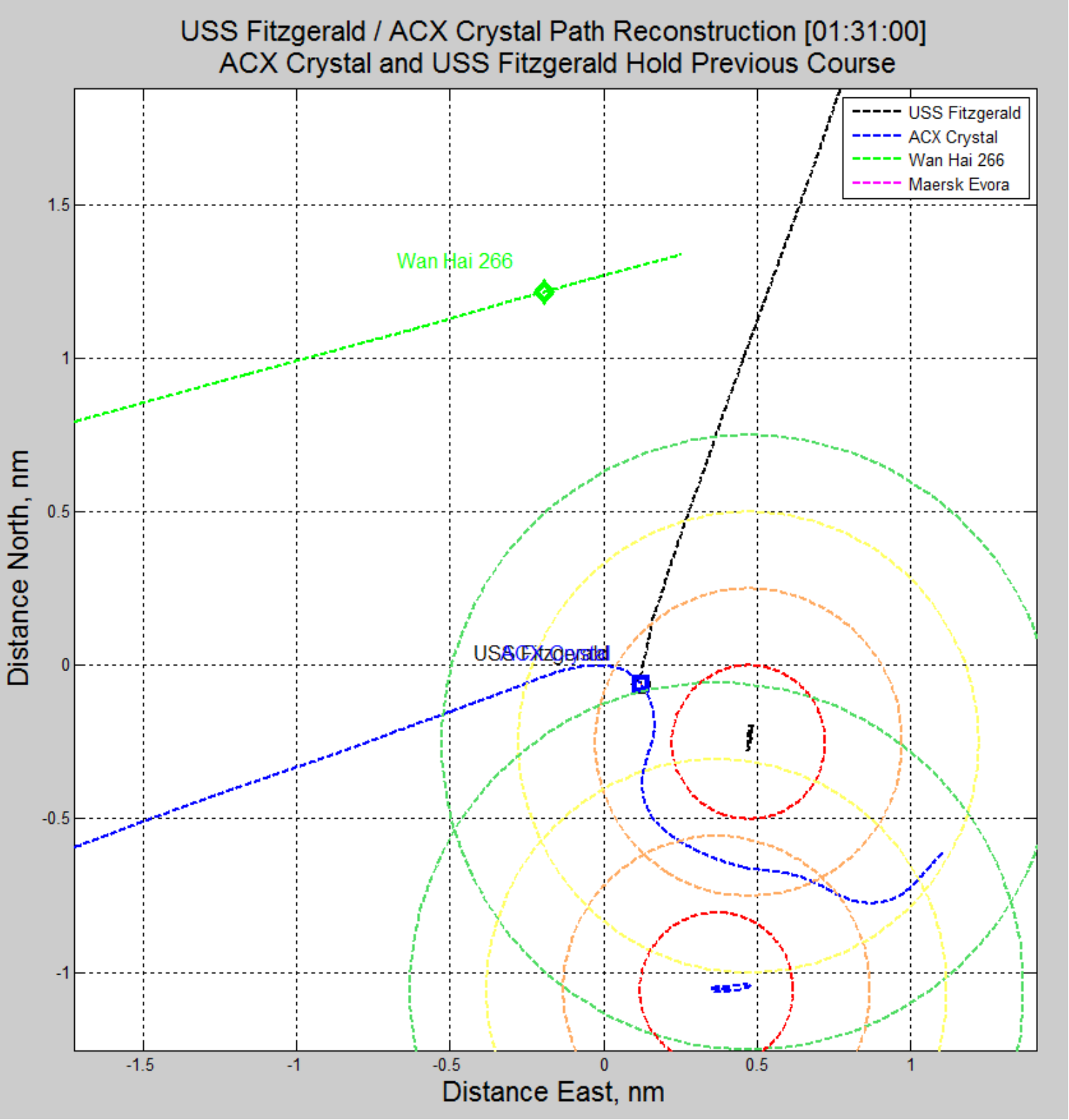
Figure A4.9: 01:31:00 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50. 0.75. and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change.
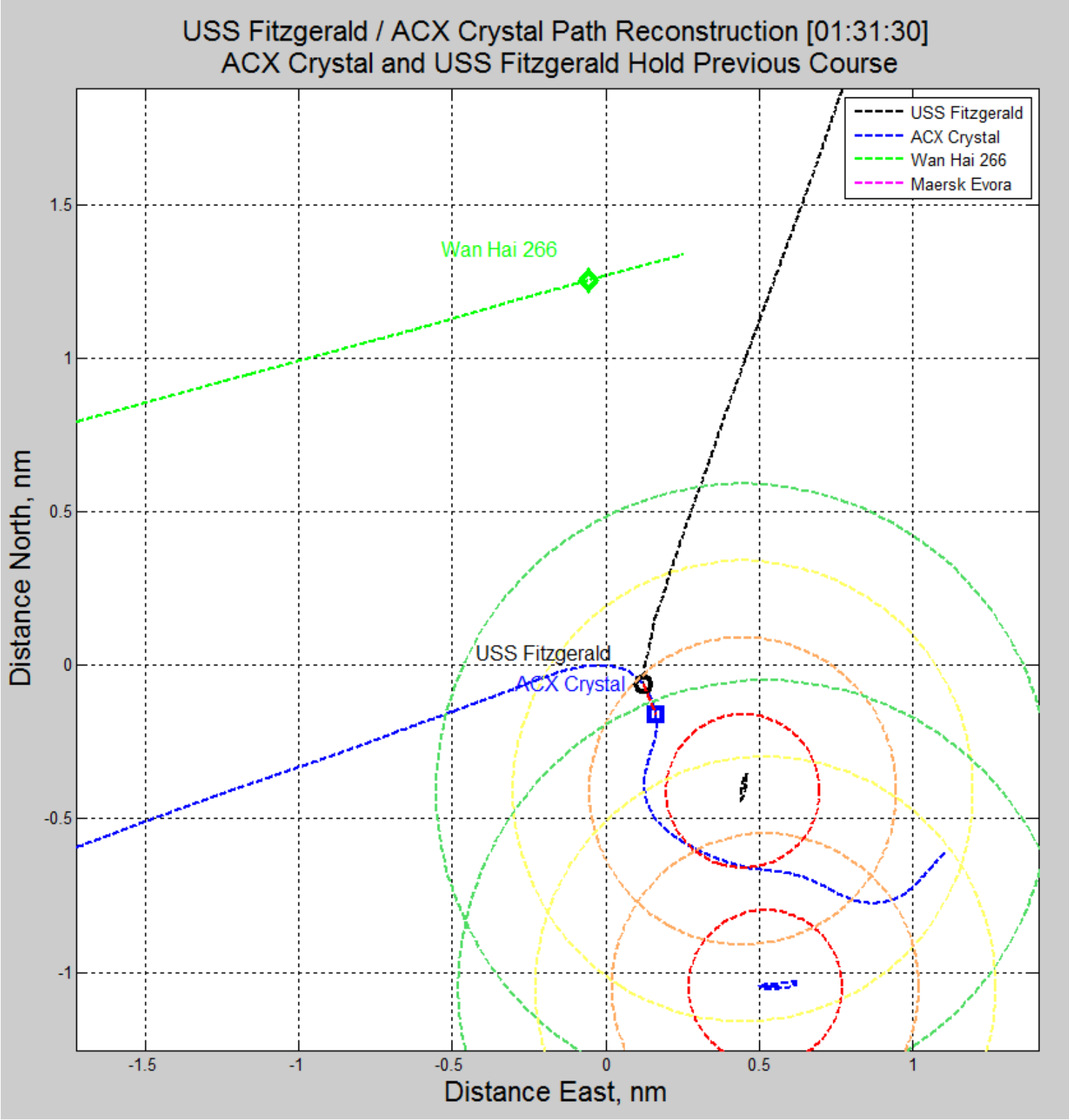
Figure A4.10: 01:31:30 Local. *USS Fitzgerald* (depicted by respective black circle, ground track, and hull outline) progresses from north to south (top to bottom) as MV *ACX Crystal* (depicted by respective blue square, ground track, and hull outline) advances from west to east (left to right). Concentric red, orange, yellow, and green circles have a respective radius of 0.25, 0.50, 0.75 and 1.00 nm. Hypothetical scenario shown assumes each vessel omits its last recorded pre-collision course change